Technical Report

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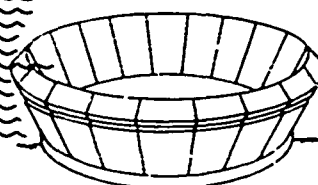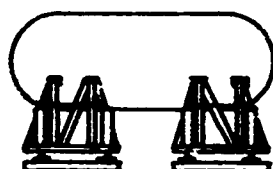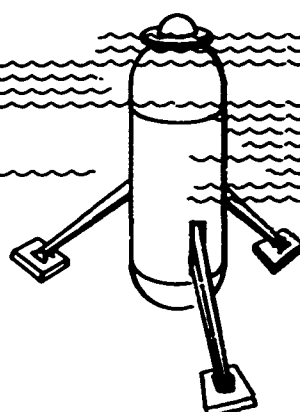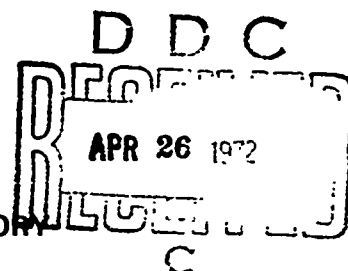SELECTION OF PRACTICAL SEAFLOOR FOUNDATION SYSTEMS

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Technical Report R-761

YF 38.535.002.01.005

by

H. G. Herrmann, D. A. Raecke, and N. D. Albertsen

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before they can be considered operational.

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INTRODUCTION

Numerous hydrophone support frames, habitats, equipment chambers, test stands, and other structures are currently deployed on the seafloor. The number of these totally submerged structures (henceforth referred to as seafloor installations) located at fixed positions on or near the seafloor, exceeds 400.[1] All such installations rely upon the seafloor and the underlying sediments for support. The mechanism by which the loads and forces of the installation, both inherent and induced, are transmitted to the seafloor is the foundation system.

The number of seafloor installations is increasing, as are their size, weight, and complexity. This increase and diversification is resulting in similar changes in foundation requirements, leading to the need for foundation systems with characteristics entirely different from those of the simple spread footing utilized almost exclusively to date.

Objective

The objective of this report is to present practical foundation system concepts developed to satisfy foreseeable requirements for seafloor installations.

Scope

Numerous planning documents suggest a variety of probable Navy seafloor installations.[2-16] The descriptions of these installations ordinarily do not specifically define the foundation requirements. However, the foundation requirements of a given installation can be inferred with sufficient accuracy to permit selection of suitable foundation types or concepts. A summary of the foundation requirements of all of the proposed installations thus forms the basis for investigating practical foundation system concepts which will satisfy foreseeable Navy needs.

In general, the configuration of foundations for seafloor installations will be controlled by a number of considerations, including: (1) relatively poor soil properties typified by low strength and high compressibility; (2) limitations on size and weight of modules which can be handled to an installation site;

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(3) severe limitations on any construction or assembly activities at an installation site; and (4) difficulty in returning to an installation to apply remedial measures. In the design process for an individual installation, consideration of specific limitations in each of these four categories, along with evaluation of other influential factors at the proposed installation site, is always necessary. In the development or evaluation of foundation system concepts, it is only necessary to consider the range over which these factors and limitations may vary.

Analysis of future foundation requirements, together with consideration of the range of values and limitations imposed by the preceding factors, suggests several concepts for foundation system configuration. With these concepts, and the basic footing foundation configuration which is already well along in development, virtually all foreseeable foundation requirements can be satisfied in a practical, workable fashion. An analysis of the characteristics of the several concepts shows that each is uniquely suited to particular situations: situations which a summarization of Navy plans shows are likely to occur in the foreseeable future.

Background

In terrestrial foundation engineering, a number of foundation types have been well developed, and design technology is readily available for each. These include both shallow and deep foundations typified by footing and pile or caisson configurations, respectively. The variations of each type and the combinations of the various types have been virtually unlimited in practice. The terrestrial foundation engineer selects a foundation type based upon the requirements of the structure and the characteristics of the site.

The same considerations exist for the seafloor situation. For selecting a suitable foundation type, or for developing concepts for foundation systems, general knowledge concerning the proposed installation and location is required. For the complete design of a specific foundation, it is, of course, necessary to have more detailed knowledge. The breadth of knowledge required for the selection of a foundation type for the seafloor is much wider than for terrestrial foundations, and includes at least the following six major considerations:

1. *Mission*: The mission of the installation determines the general performance criteria and the necessary degree of confidence in the final design. Manned installations require much greater confidence than do unmanned. In a few instances, unmanned installations containing sensitive or extremely important equipment also require high confidence. Design life must also be considered. These two criteria are quite variable for different seafloor installations. This is not true for terrestrial foundations, for which both have become relatively fixed.

2. *Site Conditions:* The geographic location, water depth, and
visibility at the proposed site affect primarily transportation, handling, and
construction considerations, which are discussed below. Other site conditions
include topography, geologic province, seismicity, and bottom currents. These
latter environmental conditions influence primarily the load induced on an
installation, which the foundation system must be designed to withstand.

3. *Physical Characteristics:* The physical size and configuration of a
foundation system are heavily influenced by the shape and dimensions of the
installation which it is to support. Other physical characteristics include sub-
merged weight, load distribution, and mass. The mass, size, and shape are
critical in determining earthquake loading conditions. Size and shape also
are important factors in determining current drag forces on an installation
which, in turn, must be resisted by the foundation system. Such transient
forces are often the major loading condition on a seafloor foundation,
because static loads are significantly reduced by buoyancy.

4. *Soil Engineering Properties:* The soil properties at the proposed
site, and their variation through the soil profile, determine, as in the terrestrial
situation, the soil response to any foundation configuration or loading condi-
tion. Of particular importance are the soil strength and compressibility, and
the time-rate variation of these two properties. The typically weak and com-
pressible soils of the seafloor present a somewhat more difficult design problem
to the foundation engineer than do their relatively competent terrestrial coun-
terparts. The evaluation of the engineering properties of a seafloor sediment
is also more difficult, and the resulting data often carry a lower degree of con-
fidence than in terrestrial work. This lower confidence must be taken into
account in the foundation selection.

5. *Deployment Capability:* The size and weight of individual modules
of a foundation system are limited by the available capability to transport these
to the proposed seafloor site, and there to position the individual modules.
Combining of modules into larger assemblies is restricted by this positioning
capability along with constraints on construction or assembly activities. Such
restraints on the design of the foundation system are unique to the seafloor
situation.

6. *Economy:* For any seafloor installation, one of the major
considerations is reliability of the installation, or degree of confidence,
with respect to satisfactory completion of its mission. The determination
of the required reliability must, however, be balanced against cost. As the
numerical requirements for reliability are increased through the realizable
range of 0.900 to 0.999, the costs typically increase by orders of magnitude,

particularly for installations in deep water. In most instances the increases are associated with at-sea operations rather than with fabrication of the actual foundation system. The cost of a partial failure can also be very high, since returning to an installation to carry out remedial work is difficult and expensive, and in a few instances, impossibly impractical. Such factors heavily influence both the selection and the detailed design of the foundation.

Portions of these six major considerations and their influences on the foundation selection process are unique to the seafloor situation and have no direct counterpart in the selection process for terrestrial foundations. For example, a seafloor installation may be placed perpendicular to a slope whereas a terrestrial structure would be leveled (perpendicular to the horizon). Thus, the influence of topography is relatively greater for the seafloor case.

Virtually all seafloor installations now in existence utilize a spread footing configuration, or a simple variation thereof.[1] This configuration has been selected because it is fairly straightforward to design, easy to handle and deploy, and basically very economical. It is also a natural choice for the small, lightweight structures primarily involved to date. However, the performance of all of these foundation systems has not been totally satisfactory. Many unsatisfactory performances appear attributable to a lack of reference to proper design considerations. Studies are currently underway to develop rational design guidelines for seafloor spread footing foundations.[17]

Pile foundations have been used extensively for offshore platforms and have been used for a few totally submerged seafloor installations. However, to date these have all been in relatively shallow water.

A number of positively buoyant seafloor structures have been deployed. For some of these, the foundation functions as a tiedown or anchorage. Although this configuration constitutes a foundation system, such systems applying a net long-term tensile load on the seafloor will not be treated extensively here. The more common case in which the foundation has sufficient submerged weight to overcome the positive buoyancy of the installation, and thus applies a net compressive load to the seafloor, is considered.

FUTURE SEAFLOOR INSTALLATION REQUIREMENTS

Many phases of the Navy's overall defense mission require the use of various types of seafloor installations. Oceanographic instruments and hydrophone arrays (such as the Saint Croix Range and BARSTUR*) are utilized extensively on the seafloor for research and routine data collection. More

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* Barking Sands Tactical Underwater Range.

elaborate acoustic systems (such as Project Artemis), installations for testing of underwater equipment (such as Deep-Submergence-Rescue-Vehicle/Simulated-Distressed-Submarine Docking Facility), and ambient-pressure habitats (such as Sealab I and II) are constructed and emplaced to meet specific defense and development requirements. Larger and even more complex installations, such as nuclear generating facilities, one-atmosphere manned stations, and fuel storage facilities may be constructed in the near future to satisfy specific research and defense objectives.[18] Each of these installation types has somewhat different foundation requirements.

The most likely types of future Navy seafloor installations have been identified, and the foundation requirements of each have been defined. This has been accomplished by summarizing information available in planning documents and technical literature, and by considering the probable extension of present seafloor installations. The best available estimates of the types of required installations and the foundation requirements of each type are presented.

Table 1 summarizes the most probable Navy seafloor installations by category. These categories are determined primarily by the nature or function of an installation and secondarily by the probable size of an installation. A more complete compilation and description of existing seafloor installations is given in Reference 1.

Small Instruments and Sensors

These installations are typified by the many bottom-sitting hydrophone arrays deployed for investigating the acoustic properties of the ocean environment, for use with submarine detection and communication systems, and for tracking in underwater test ranges. Bottom-resting instruments to measure other environmental properties, such as current velocity, temperature and salinity, corrosion effects, and soil properties, are included in this category. These installations are ordinarily open-frame structures mounting appropriate instrumentation and power supplies. Examples of two typical configurations are shown in Figures 1 and 2. Typical dimensions for installations in this category are less than 12 by 12 feet in plan and 15 feet in elevation. A typical submerged weight is 400 pounds, although weights may go as high as 4,000 pounds.

Nearshore, deep-water sites (to water depths of 20,000 feet); seamount crests and slopes; and deep-water slopes are three locations of particular interest for installations of this category. The seafloor in these locations varies from weak and compressible cohesive soils to sound rock. The foundation requirements of such installations are basically rather simple: (1) some form of vertical

support providing sufficient bearing capacity and minimizing total and differential vertical movement (settlement); (2) lateral support to prevent skidding or other horizontal movements; and (3) a simple foundation configuration providing for one-step deployment. Simplicity is also advantageous because these installations are very often deployed in groups, with as many as 30 or 40 identical installations deployed in a specified pattern. The actual tolerance for positioning of an individual installation may be as small as 100 feet or as large as 1 mile. However, it is often necessary to know the actual final position of such an installation with much greater accuracy, particularly with reference to the other similar installations within the pattern. This does not significantly affect the foundation requirements.

The fact that many of the sites are located on slopes requires, for the more sensitive installations, either careful control of orientation during deployment or some means of gimbaling or leveling to ensure vertical orientation of the instrumentation both initially and during the design life. The strictest requirements for vertical orientation within this category are on the order of ±10 degrees. However, absolute orientation is usually not nearly as critical as is the prevention of any variation in orientation during the lifetime of such a sensitive installation. Design life for all of these installations has typically been specified as 5 years, although recent experience[1] would indicate a design life of from 10 to 20 years to be more applicable for many. Several hundred installations fitting this category have already been utilized on the seafloor. Available information indicates a continuing need for such structures.

Instrument and Equipment Packages

The installations in this category differ from those of the previous category primarily in size and in sophistication of instrumentation, rather than in function or nature. Examples include underwater towers (such as the Navy camera towers at San Clemente Island and the Project AFAR* towers, Figure 3), underwater electronic chambers (such as the junction chamber at SCARF** and the DOBACS*** in the Bermuda Range), and underwater navigation equipment utilizing larger power sources. These installations will generally be substantially heavier (submerged weights ranging from 4,000 to 20,000 pounds) and physically larger (maximum structural dimension as large as 200 feet) than those in the preceding category.

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* Azores Fixed Acoustic Range.

** Santa Cruz Island Acoustic Range Facility.

*** Deep Ocean Basin Acoustic Cable Source.

Table 1. Probable Navy Seafloor Installations

Category	Nature/Mission	Water Depth (ft)	Maximum Dimension (ft)	Submerged Weight (lb)	Probability of Emplacement
Small instruments and sensors	unmanned, small instrument packages for oceanographic research and ASW	to 20,000	to 15	0 to 4,000	numerous installations *certain*
Instrument and equipment packages	unmanned, larger installations for oceanographic research and ASW	to 6,000	15 to 200	4,000 to 40,000	many installations *certain*
Test facilities	unmanned specialized installations for in-situ testing of equipment and procedures	to 600	to 60	6,000 to 700,000	several *likely*
Bulk storage	unmanned, large facilities for storing fuels and other bulk supplies for fleet use	to 600	to 300	to 20,000,000	several *likely*
Power sources	unmanned power sources, including nuclear reactors	to 20,000	to 50	to 800,000	many small *certain*; several large reactors *likely*
Manned installations	manned, one-atmosphere and ambient pressure habitats or stations	to 6,000	to 70	to 80,000	several *likely*

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Figure 1. Typical dual hydrophone array structure. (From Reference 19. Photo courtesy of AC Electronics.)

Figure 2. STU (Submersible Test Unit) with RTG (radioisotope thermoelectric generator) power source installed.

Seamount crests and slopes, and nearshore deep-water slopes (to water depths of 6,000 feet) are typical sites for these installations. These sites exhibit from negligible to moderate slopes (30 degrees appears to be a maximum). The seafloor ranges from weak and compressible cohesive sediments at the deeper sites to sand and bedrock at the shallower sites and on seamount crests.

These installations are typically one-of-a-kind and are commonly both sophisticated and expensive. These characteristics and the more stringent requirements for foundation performance usually make it necessary to perform a more detailed site selection and analysis. Performance requirements include: (1) high confidence in an adequate bearing capacity, (2) minimum

tilting caused by differential settlement (no more than 1-1/2 degrees of tilting can be tolerated in some cases), and (3) prevention of lateral motions or skidding. A fairly simple foundation configuration allowing for one-step deployment is usually required. Control of position (tolerances as small as 100 feet are required) during deployment can be critical, because these installations are often connected by electrical cable to other structures in the vicinity.
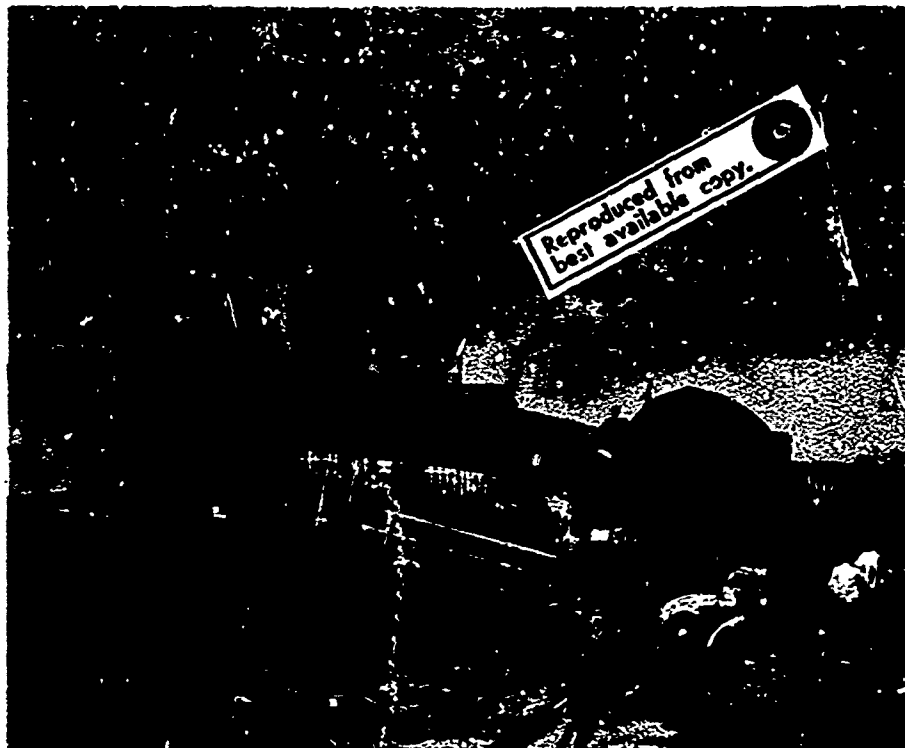
Figure 3. Project AFAR "November" Tower before emplacement in vertical orientation.

The design life of these installations is in the 10- to 25-year range. The importance and value of these installations normally would allow for returns to the installation after deployment in order to investigate apparent performance problems or to carry out minor remedial operations. Many dozens of installations fitting this category have been deployed on the sea-floor. The need for these installations is increasing—a trend made possible by improving technology.

Test Facilities

Submerged installations are utilized by the Navy to test equipment and techniques designed for deployment or use in the world ocean. These installations are specialized, one-of-a-kind facilities. Examples include missile launchers (such as Pop-Up Launcher II, Figure 4), submarine-docking test facilities (such as the Navy's Simulated Distressed Submarine at San Clemente Island and the Perry-Link Hydrolab), and simulated habitats (such as the SEACON structure). The physical characteristics of each are quite different, with the major dimension ranging from 10 to 60 feet and submerged weights ranging from 6,000 to 700,000 pounds. Loading conditions are also quite diverse, as some installations are subjected to large (200,000-pound) dynamic loads and impact loads from various directions in addition to the static loads due to submerged weight.

These installations are typically located in shallow water (less than 600 feet) and near shore. Sites are usually carefully surveyed to select those with only gentle slopes and competent soil types, such as sands and rock. Geographically, these installations are typically located just offshore the continental United States.

Because all are very specialized installations, the requirements for foundation performance are often well defined; however, the requirements for the various installations are diverse. Typical requirements include: (1) high confidence in bearing capacity under both static and dynamic conditions, (2) minimum differential settlements (requirements as stringent as less than 1/8-inch differential movement), and (3) prevention of lateral motions under static, dynamic (oscillating), and impact loading. Foundation configurations can be more complex, because most are in shallow water. Control of position during deployment or construction is critical (tolerances can be less than 1 foot), since these installations are often multimodule.

Design life for these installations is often short (1 to 4 years); however, a few are used over longer periods (to 15 years). The typical locations and natures of these installations allow for relatively easy return for inspection and remedial work. Such installations are often subjected to major modifications during their life, which in some cases can necessitate modification of the foundation system.

Several installations fitting this category are currently deployed on the seafloor. The need for such facilities is expanding along with the requirements for, and development of, seafloor construction techniques and equipment.
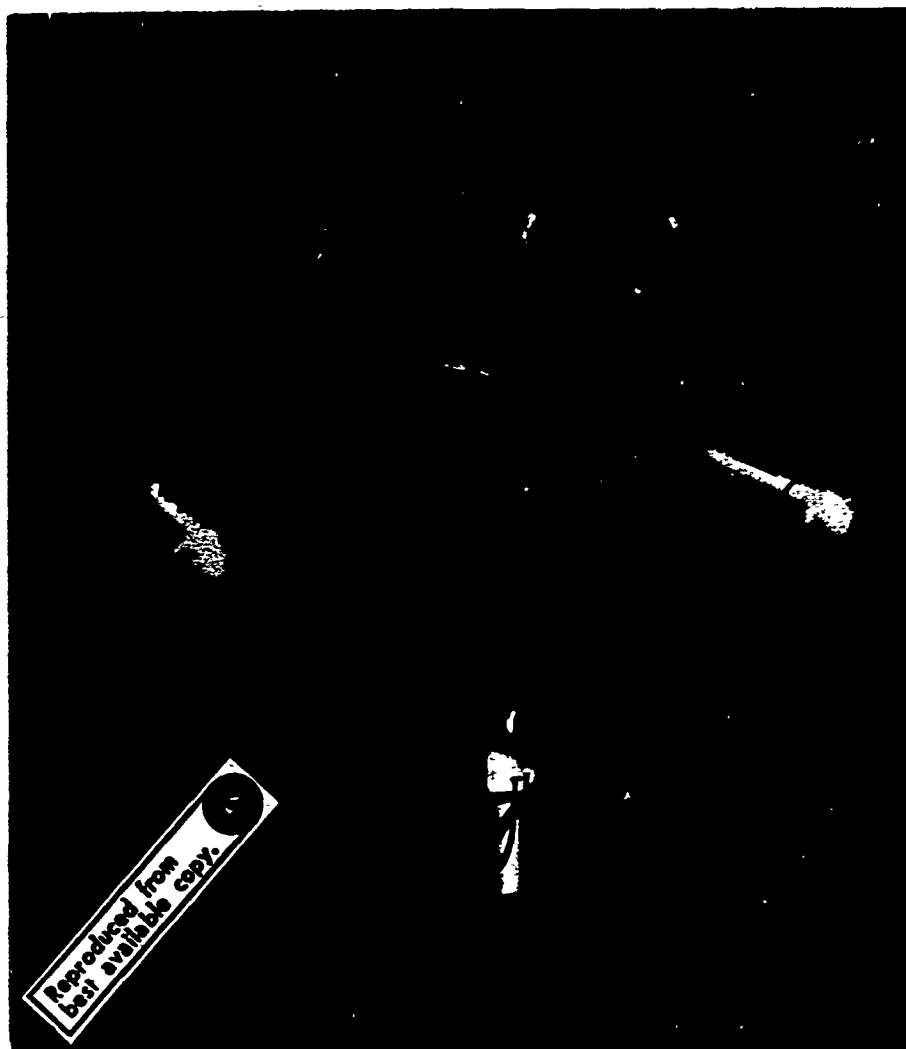
Figure 4. Pop-Up Launcher II. (From Reference 20.)

Bulk Storage

Submerged bulk storage installations are of interest to the Navy from both strategic and economic standpoints. The bulk storage of fuels for the Fleet is of primary interest. Examples include movable installations with

capacities of up to 25,000 barrels and fixed storage (similar to Khazzan Dubai 1, Figure 5) with capacities of up to 600,000 barrels. Fixed installations are typically large, rigid installations with submerged weight very low relative to their size. The foundation loading varies with the fuel level because of the difference in unit weight between the fuel and the seawater which it displaces during filling. The other major loading condition results from drag forces caused by ocean currents. Movable facilities are subject to the same variable loading conditions. The effects of these loading conditions are relatively greater because of the overall near-neutral buoyancy of the movable facilities.

Installations in this category could be located virtually anywhere in the world ocean at shallow water depths (less than 600 feet). The sites are typically level (within 2 degrees) and exhibit soil properties ranging from cohesive shelf deposits to granular soils and possibly sound rock. Detailed survey and analysis of sites are performed for fixed installations. Similar surveys are sometimes available for the sites of movable facilities.

The foundation requirements of the two classes are somewhat different. The fixed installations require high confidence in adequate bearing capacity and prevention of lateral motions or overturning. These installations are unaffected by settlement or differential settlement except where this would cause racking or overstressing in the structure or in connections to it. The movable installations differ from the fixed facilities in that they may have much less submerged weight for a similar-sized structure. As a result, the foundation must provide for more relative resistance to overturning and lateral movement. These installations are sometimes made of flexible members, and thus can tolerate very large differential settlements.

The requirements for control of position during construction are typically only moderate for fixed installations unless modular construction is used. For movable facilities, there may be little position control (tolerances as large as 1 mile for individual units) during deployment. Where control is minimal, the deployment capability will likely also be minimal, consisting of a simple "drop-in-place." Design life for such deployments may be short (ranging from 6 months to several years). Design life for the fixed facilities may be much longer (over 20 years). Many of these installations will be in shallow-water locations which allow for return for inspection and remedial work if required. Fuel storage in fixed seafloor facilities has been used in shallow water by petroleum companies where economically justified. The French are planning facilities of moderate size in deeper water.[22, 23] Smaller movable facilities have been tested by the Navy. The actual need for such facilities by the Navy is dependent upon numerous factors; however, a demonstrable capability in the next 5 years appears desirable.

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Figure 5. Khazzan Dubai I. (From Reference 21. Photo courtesy of Chicago Bridge and Iron Company.)

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Power Sources

A number of seafloor installations require large amounts of electrical power for such purposes as navigation beacons, ASW surveillance systems, communication systems, manned habitats, and seafloor work equipment.[24] For short missions (less than 6 months) batteries and fuel cells can be used. For longer term or larger power requirements, power may be supplied from shore, surface, or near-surface based power sources with underwater transmission cables. The on-site portions of such power systems would ordinarily be an integral portion of other installations and would not affect foundation selection or design except from a weight standpoint. Fuel cells are compact (8-foot cube for a 50-kw, short-duration unit), nearly neutrally buoyant, can be used to any water depth, and can be designed to operate in various inclined attitudes up to 45 degrees. Batteries have characteristics similar to fuel cells except that they have significant submerged weight. Power brought in by electrical cable may require transformers. The characteristics of this system are between those of fuel cells and batteries with additional restrictions on positioning. There may be an additional load imposed by the electrical cable which must be resisted by the foundation. Small (less than 100 watts) long-term needs can be satisfied by radioisotope thermoelectric generators (RTGs). These are compact (4-foot cube), heavy (to 8,000 pounds) units that influence foundation requirements in a manner similar to batteries.

Where larger, long-term power requirements exist at remote sites, and a seafloor source is necessary, bottom-sitting nuclear reactors may be required. These would likely be individual installations with specific foundation requirements. Weights would be high (100 to 400 tons for electrical capacities ranging to 20 Mw) although much of this could be offset by the buoyancy of oversized pressure-resistant housings designed for water depths to 20,000 feet. Vertical configurations are likely (heights to 50 feet and diameters to 30 feet). Such installations can tolerate moderate settlement and tilting (up to 15 degrees). A high reliability in the stability of the installation is required.

Typical sites for such reactors would be located some distance offshore and could be anywhere in the oceans, although locations of strategic interest, such as seamounts and mid-oceanic ridges, seem most likely. Soil properties in these areas would often be sound, irregular rock, although materials ranging to weak and compressible cohesive soils are possible. Sites for such installations would likely be investigated in detail. These structures require moderate control of positioning during placement. Design life for the installation would vary from short- to long-term (10 to 15 years) deployments.

Small power sources, including RTGs, batteries, and fuel cells, are used fairly regularly on the seafloor. The use of nuclear reactors at a few installations within the next 10 years seems likely.

Manned Installations

The installations in this category differ from those of the previous sections primarily on the basis of required reliability and performance. Examples of these installations include one-atmosphere stations (such as Project Atlantis, Figure 6) and ambient-pressure habitats (such as Tektite, Figure 7). These installations are of intermediate size and weight (typical lateral dimensions in the 10- to 70-foot range, with submerged weights ranging from 3,000 to 80,000 pounds).
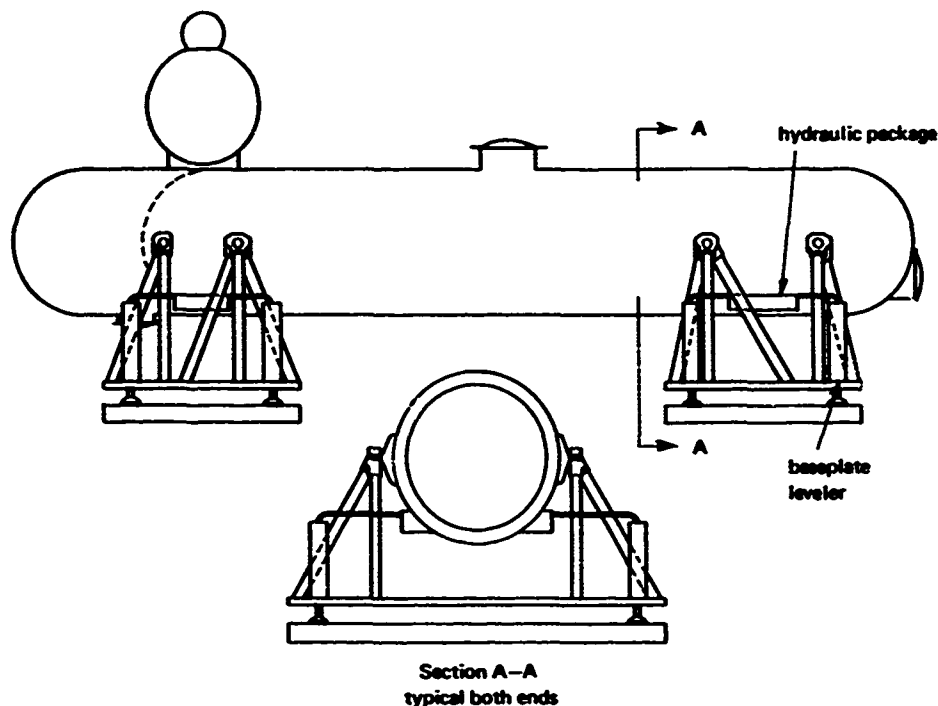
Figure 6. Proposed Project Atlantis manned station. (From Reference 25.
© University of Miami and Chrysler Corporation. Used by permission.)

Typical locations include the continental shelves and seamount crests at water depths less than 600 feet. Sites in water depths to 6,000 feet in regions bordering the above locations are also possible. These sites would probably be located near the United States. The sites would be thoroughly investigated and would typically consist of level terrain and granular soil. A few sites on rock and possibly on cohesive soils are also likely, although requirements for reasonable visibility usually exclude the latter. Site preparation (leveling) and rather precise control of position during emplacement will be typical.

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Figure 7. Project Tektite habitat. (From Reference 26. © G. E. Re-entry and Environmental Systems Division, Ocean Systems Programs, Philadelphia, Pa. Used by permission.)

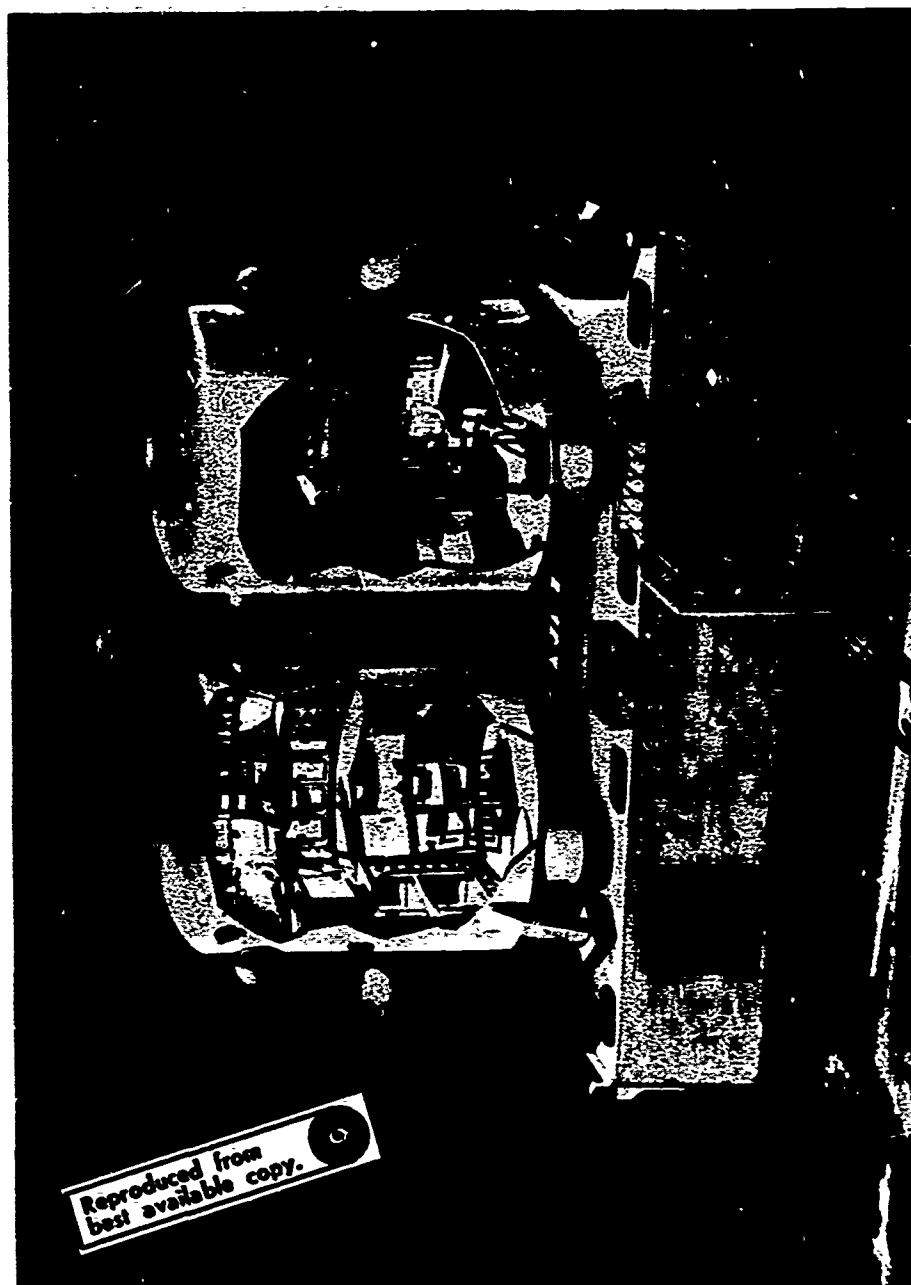The two basic criteria for performance are: (1) extremely high confidence in the stability of the site and the foundation (including bearing capacity, overturning, and lateral stability) under all foreseeable circumstances (including earthquake, ocean currents, and other possible extreme loading conditions), and (2) minimum tilting as a result of site topography or differential settlement (tilting of more than 1 degree can cause difficulties). Design life for these installations is usually short (6 months to 1 year), although the same structure may be redeployed at different locations. Precise monitoring of foundation performance and means for taking remedial steps are usually available.

Over a dozen habitats have been used in continental shelf water depths during the past decade.[1] All but one were ambient-pressure habitats; the exception was in very shallow water. The number of these habitats is increasing rapidly. Depths are limited primarily by diver capabilities, except in the case of one-atmosphere manned stations. A number of these are to the design stage, and it seems likely that several will be in use by the end of the decade.

Summary

The six installation categories described above encompass, either singly or in combination, virtually all Navy seafloor installations in the foreseeable future. To select a suitable foundation system, the foundation requirements of an installation must be defined in terms of requirement parameters, determined by the mission and probable installation configuration. Many foundation requirement parameters can be proposed; however, the most important are: (1) required reliability (confidence level), (2) sensitivity to tilting, (3) submerged weight and (4) size (mean plan dimension).

In Table 2, the six installation categories are redefined in terms of these foundation requirement parameters. The range for each parameter is divided into three levels. For several categories, a wide variation is indicated for some parameters. For example, in Category III, Equipment Test Facilities, the sensitivity may be low, moderate, or high, depending upon the mission of the particular installation. This simply represents the fact that individual installations within a category may be quite diverse. This diversity is demonstrated in Table 3, which shows all possible combinations of values for the four foundation requirement parameters. Table 3 shows that of these 81 possible combinations, only 19 represent real or foreseeable requirement combinations as determined from Table 2.

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Table 2. Foundation Requirement Parameters for Each Installation Category

Installation Category	Foundation Requirement Parameters			
	Reliability	Sensitivity	Submerged Weight	Size
I. Small Instruments and Sensors	moderate (0.9)	low (>±5 deg)	small (<2 tons)	small (<12 ft)
II. Large Instrumented Installations	moderate to high (0.9 to 0.99)	moderate (±5 to ±1 deg)	medium (2 to 20 tons)	medium (12 to 40 ft)
III. Equipment Test Facilities	high (0.99)	low to high (>±5 to <±1 deg)	medium to large (2 to >20 tons)	medium (12 to 40 ft)
IV. Bulk Storage	moderate (0.9)	low (>±5 deg)	small to large (<2 to >20 tons)	large (>40 ft)
V. Power Sources	moderate to high (0.9 to 0.99)	low (>±5 deg)	medium to large (2 to >20 tons)	medium to large (12 to >40 ft)
VI. Manned Installations	very high (0.999)	high (<±1 deg)	medium to large (2 to >20 tons)	medium to large (12 to >40 ft)

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Table 3. Determination of Foundation Classes From Requirement Parameters of Each Installation Category

Theoretically Possible Parameter Combinations	Possible Reel Combinations	Requirement Parameters				Foundation Class[a]	Number of Foundations Needed	Value of Each Installation ($K)
		Size	Weight	Sensitivity	Reliability			
1	C1	small	small	low		A[b]	>100	<20
2		medium						
3	C2	large				E	<10	20 to 5,000
4		small	medium					
5	C3	medium		low		C	<10	20 to 5,000
6	C4	large				C	<10	20 to 5,000
7		small	large					
8	C5	medium				C	<10	20 to 5,000
9	C6	large				C	<10	20 to 5,000
10		small	small	moderate				
11		medium						
12		large						
13		small	medium					
14	C7	medium	medium	moderate	moderate	C	10 to 100	20 to 5,000
15		large						
16		small	large					
17		medium						
18		large						
19		small	small	high				
20		medium						
21		large						
22		small	medium					
23		medium	medium	high				
24		large						
25		small	large					
26		medium						
27		large						
28		small	small	low	high			
29		medium						
30		large						

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Table 3. Continued

Theoretically Possible Parameter Combinations	Possible Real Combinations	Size	Weight	Sensitivity	Reliability	Foundation Class[a]	Number of Foundations Needed	Value of Each Installation ($K)
31		small						
32	C8	medium	medium	low		F	<10	>5,000
33	C9	large				E	<10	20 to 5,000
34		small						
35	C10	medium	large			F	<10	>5,000
36	C11	large				F	<10	>5,000
37		small	small					
38		medium						
39		large						
40		small						
41	C12	medium	medium	moderate	high	G	10 to 100	20 to 5,000
42		large						
43		small						
44	C13	medium	large			H	<10	>5,000
45		large						
46		small	small					
47		medium						
48		large						
49		small						
50	C14	medium	medium	high		H	<10	>5,000
51		large						
52		small						
53	C15	medium	large			H	<10	>5,000
54		large						
55		small	small	low				
56		medium						
57		large						
58		small	medium		very high			
59		medium						
60		large						

continued

Table 3. Continued

Theoretically Possible Parameter Combinations	Possible Real Combinations	Size	Weight	Sensitivity	Reliability	Foundation Class[a]	Number of Foundations Needed	Value of Each Installation ($K)
61		small	large	low	very high			
62		medium	large	low	very high			
63		large	large	low	very high			
64		small	small	low	very high			
65		medium	small	low	very high			
66		large	small	low	very high			
67		small	medium	moderate	very high			
68		medium	medium	moderate	very high			
69		large	medium	moderate	very high			
70		small	large	moderate	very high			
71		medium	large	moderate	very high			
72		large	large	moderate	very high			
73		small	small	moderate	very high			
74		medium	small	moderate	very high			
75		large	small		very high			
76		small			very high			
77	C16	medium	medium	high		K	<10	>5,000
78	C17	large	large			J	<10	>5,000
79		small	small					
80	C18	medium	large			K	<10	>5,000
81	C19	large	large			K	<10	>5,000

[a] A foundation class represents a combination of requirement parameters, or a group of nearly identical combinations, that must be considered in the process of investigating, developing, and selecting foundation concepts. See Table 4 for identification of installation categories that will fit foundation classes.

[b] Example — class A has the following requirements: Size   — small
                                                       Weight   — small
                                                       Sensitivity — low
                                                       Reliability — moderate

Table 4. Foundation Classes, Requirement Parame

(Definitions of foundation requirement parameter values)

Foundation Class	Foundation Requirement Parameters					
	Size	Weight	Sensitivity	Reliability	I. Small Instruments and Sensors	II. Large Instrumented Installations
A	small	small	low	moderate	●	
B	large	small	low	moderate		
C	large	large	low	moderate		
D	medium	medium	moderate	moderate		●
E	large	medium	low	high		
F	medium	large	low	high		
G	medium	medium	moderate	high		●
H	medium	large	high	high		
J	large	medium	high	very high		
K	large	large	high	very high		

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n Classes, Requirement Parameters, and Uses

n requirement parameter values are given in Table 2.

	Installation Categories				
rge Instrumented Installations	III. Equipment Testing Facilities	IV. Bulk Storage	V. Power Sources	VI. Manned Installations
		•		
		•	•	
•				
	•		•	
	•		•	
•	•			
	•			
				•
				•

In the process of investigating or developing concepts for foundation systems, it is desirable to work with a minimum number of combinations. Each of the 19 combinations represents a separate set of requirement parameters; however, the combinations are not necessarily unique from the standpoint of the foundation systems that will satisfy the requirements. Therefore, the 19 combinations were analyzed to determine which combinations are separately distinct and form classes by themselves, and which combinations can be grouped together to form classes. The analysis of the foundation systems required for the 19 combinations shows that only 10 unique foundation classes exist. Table 3 lists these 10 foundation classes, qualitative estimates of the number of future installations exhibiting that combination of foundation design parameters, and an estimate of the relative value or importance of an installation within that class. Table 4 restates the requirement parameters for the 10 foundation classes and shows which class will satisfy each installation category. These 10 foundation classes represent the combinations of foundation requirement parameters likely to occur within the Navy in the near future.

To determine the optimum foundation system (such as multiple pile, spread footing, or mat) for each class, it is necessary to consider foundation design constraints, both environmental and technological, in addition to the design parameters of each foundation class. These design constraints are defined, their range of influence discussed, and their effect on foundation system selection determined in the next section.

FOUNDATION DESIGN CONSTRAINTS

The principal constraints which control the selection and design of a foundation system satisfying the design parameters of a given foundation class are related to the sediment engineering properties, the site conditions, and the deployment capabilities. The sediment engineering properties that control foundation selection and design are the shear strength and compressibility characteristics. The site conditions of major interest include the topography, bottom currents, water depth, and seismicity at the site. However, in the present study, the effects of seismicity of a site upon foundation selection and design have not been specifically considered, because it is believed that at present the only basis for decision would be a "go/no-go" choice. The deployment capabilities can be divided into positioning, load-handling, and construction capabilities. One other factor which can affect foundation design is the nature, or properties, of materials selected for fabrication of foundation elements.

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Generally, the environmental constraints (sediment properties and site conditions) influence primarily the design parameters reliability and sensitivity, whereas the technological constraints (deployment capabilities and materials) affect the weight and size of an installation. This is illustrated in Table 5, which shows qualitatively the degree of influence which each design constraint exerts upon the various design parameters.

Table 5. Relative Influences of Design Constraints on Design Parameters

Design Constraints	Design Parameters			
	Reliability	Sensitivity	Weight	Size
Sediment properties	X[a]	X	X	+[b]
Topography	X	X	O[c]	O
Bottom currents	+	O	O	O
Water depth	+	O	+	+
Positioning	O	O	+	O
Load handling	O	O	X	X
Construction capabilities	O	O	X	X
Materials	O	O	X	+

[a] X = major influence.

[b] + = intermediate influence.

[c] O = minor influence.

To define the nature and magnitude of the foundation design constraints, available information has been collected and analyzed in the following areas:

1. Distribution and engineering properties of seafloor sediments

2. Large-scale topographic features (macrotopography) and surface roughness (microtopography) of the seafloor

3. Distribution and magnitude of bottom currents

4. Surface, and surface-to-bottom, positioning capabilities

5. Load-handling capabilities

6. Seafloor construction capabilities

7. Materials for seafloor foundations

Where appropriate, the available information has been summarized in quantitative form to the extent possible, and future capabilities or states of knowledge were considered in assessing the constraints on seafloor foundation engineering. The results of these literature surveys are presented in this section, as well as in several appendixes.

Environmental Factors

Sediment Properties. The bulk of available information concerning the distribution and physical properties of seafloor sediments has been obtained by marine geologists and oceancgraphers, who do not ordinarily measure or investigate the engineering properties of the sediments. However, certain tentative correlations between sediment type and the engineering properties of the sediment are available. Appendix A presents detailed information concerning the classification of seafloor sediments, the distribution of sediment types in the world ocean, and the engineering properties of seafloor sediments. In this section, some general conclusions are drawn from the information in Appendix A, and the effects of sediment properties upon foundation selection and design are discussed.

The most significant general conclusion that can be drawn from Appendix A is that seafloor sediments frequently are considerably weaker and more compressible than is common for terrestrial soils. However, two facts must be considered: (1) most sediment sampling techniques permit a maximum penetration of only about 10 feet into the sediment profile; and (2) most sampling techniques produce considerably disturbed samples, whose properties may only roughly correlate with those of the material in situ. There is considerable theoretical justification, and a moderate amount of experimental evidence, for expecting the soil properties to improve (increasing shear strength and decreasing compressibility) with increasing depth in the sediment profile. There is also a large volume of evidence showing that the engineering properties of undisturbed sediment are often considerably superior to those measured from disturbed samples.

Sediments which have been investigated to an appreciable extent (such as continental shelf and slope sediments) do not appear to have any unique characteristics that invalidate the use of terrestrial soil mechanics

theories for seafloor foundation design.[27] However, the sediment properties are commonly at, or just beyond, the extreme ranges of terrestrial experience. Thus, applicable empirical data and well-documented foundation performance records for terrestrial situations are scarce. Such information for seafloor situations is also very limited. The lack of information about the variation of sediment properties with depth in the soil profile, and the scarcity of information concerning the engineering properties of deep-ocean sediments, also limit the level of confidence that can be placed in foundation design using terrestrial procedures. Thus, foundations for seafloor installations will continue to be designed using very conservative procedures until case histories and the results of further research are available.

It appears that adequate bearing capacity for seafloor installations can be provided with careful analysis and foundation design, coupled with careful sediment sampling and testing. Most installations will probably experience large total settlements because of the high compressibility of seafloor sediments; the likelihood of large differential settlements is also great. Thus, installations should be designed to provide as even a load distribution as possible to minimize differential settlements. It may also be necessary to provide means of compensating for such settlement in order to minimize the adverse effects, particularly secondary stresses in the structure.

Sediment distribution is related in a general way to water depth. Shallow-water sediments (continental shelf) are most often sands and silts; intermediate-depth sediments (continental slope) are silts and clays; and deep-water sediments are clays and oozes. This distribution can also be related to macrotopography. The general rule is, the steeper the slope, the larger the grain size. For example, very steep slopes are typically rock, whereas the flat ocean basins are fine-grained clays and ooze. Also, although the correspondence is not perfect, the strength and compressibility of seafloor sediments is related to sediment type: sands can ordinarily be considered as strong and incompressible, clays and oozes as weak and compressible, and silts as of intermediate strength and compressibility. There are numerous exceptions, but these general relationships are sufficiently accurate for planning purposes. Thus, the design constraints imposed upon foundation selection by seafloor sediments will be considered to be directly related to sediment type. For the present purpose, four sediment categories will be utilized: (1) weak and compressible cohesive soils, (2) competent cohesive soils (average shear strength in upper 1 foot greater than 1 psi), (3) sands, and (4) rock.

Topography. The topographic features of the seafloor can be divided into three broad categories: (1) macrotopography, (2) microtopography, and (3) surface roughness. The demarcations between the categories will arbitrarily be set at 60 feet (10 fathoms) and 5 feet; in other words, features with vertical

relief greater than 60 feet will be classified as macrotopographic features, and those with relief between 60 and 5 feet, as microtopographic features. Features with relief less than 5 feet are classed as surface roughness. Detailed descriptions of the topographic features of the seafloor are contained in Appendix B. In this section, general conclusions are drawn from Appendix B, and the effects of topography upon foundation design are discussed.

The ocean floor was formerly believed to be flat and featureless, a misconception fostered by hydrographic charts based on widely scattered depth soundings. In the drawing of the charts, a uniform slope is assumed to exist between two soundings. If the distance between the soundings is too great, significant features may be "lost." For example, soundings could be made on either side of a canyon or mountain. The development of modern depth-sounding and recording techniques has shown that seafloor topography is essentially as variable as that of dry land. The major topographic features of the seafloor are: (1) the continental shelf, (2) the continental slope, (3) the continental rise, (4) the abyssal plains and hills, (5) oceanic ridges and rises, (6) trenches, and (7) volcanic cones. Superimposed upon these major features are numerous hills, ridges, basins, and valleys that can also be classed as macrotopographic features. In general, the microtopography and the surface roughness are directly related to the macrotopographic features upon which they are superimposed; in other words, where the macrotopography is rough, the seafloor surface is generally rough. Also, the microtopography and surface roughness generally decrease with increasing water depth.

The topography at a given site may affect a proposed installation in two major ways:

1. If the site is not perfectly level and flat, the installation may be tilted with respect to a horizontal plane.

2. If the slope is great enough, either the installation may skid down the surface of the slope, or a local slope failure may occur when the additional load is placed thereon.

The effects of these eventualities upon foundation design are discussed below.

The topography at a given site determines the initial inclination of an installation from a horizontal plane; thus an installation will rest approximately at the same inclination as the local topographic slope. The inclination of an installation may also be caused, or increased, by the surface roughness (outcrops or ripple marks) at a site. The inclination of an installation from a horizontal plane may have several adverse effects which must be considered in the design of the foundation. If the inclination is too great, the installation may overturn immediately. This can be prevented by careful site survey so that the probable maximum slopes are known and anticipated in the design,

by designing the installation to have a low center of gravity, and by increasing the minimum overall lateral dimension of the foundation. For lesser inclinations, the safety of the installation may still be affected by large secondary stresses in the structure, and the operation of the equipment or personnel within the installation may be impaired.

The inclination of a structure also affects the interaction between the foundation and the underlying sediments. Most footing and mat foundations are designed with the assumptions of uniform distribution and equal magnitude of soil pressure under each foundation element. If the installation lands on a slope, the soil pressure under footings on the low side will be greater than under footings on the high side. The higher pressures may cause relatively greater settlements on the low side, further increasing the inclination of the installation. For structures with a high center of gravity, overturning caused by local overstressing of the soil and bearing-capacity failures may become a hazard. For most other structures, the differential settlement will be detrimental to proper functioning.

The likelihood either that an installation will skid down the surface of a slope or that a local slope failure will occur is difficult to evaluate. To prevent skidding, the resistance to lateral motion may be increased by increasing the depth of embedment of the foundation or by the use of anchors. Where the total foundation cannot be more deeply embedded, the effective embedment depth may be increased by the use of metal plates or short piles around the perimeter of the foundation elements. At a site where the probable maximum slope is so great that slope failure may result from the additional load imposed by an installation, it may be possible to locate the installation in an area of lesser slope within the site. However, several emplacement attempts may be required to accomplish this; if the attempts are unsuccessful, a decision must be made either to accept the risk of slope failure, or to abandon the site. The capability to stabilize a potentially hazardous underwater slope does not exist at present.

It is apparent that seafloor topography and surface roughness are, in general, irregular and variable. The irregularity and variability appear to be more pronounced at shallower depths. This circumstance significantly affects seafloor foundation engineering, since the majority of seafloor installations of the near future will be placed in relatively shallow water.

The degree of constraint imposed upon foundation selection and design by seafloor topography can be expressed by a combination of two factors: (1) the probable overall slope that exists at a site, and (2) the magnitude of the surface roughness. Four ranges of overall slope will be considered: less than 1-degree slope, 1- to 4-degree slope, 4- to 10-degree slope, and greater than 10-degree slope. Within each range, the surface roughness will be classed

as small if the magnitude of the roughness is less than 1 foot, and as large if the magnitude is greater than 1 foot. These categories are useful in the process of selection of foundation systems. Manned and other sensitive structures typically require a level operating attitude within 1 degree of the horizontal. Structures with other missions are less sensitive to the effects of tilting; however, at attitudes greater than about 4 degrees relative to horizontal, differential stressing of the underlying soil becomes a serious consideration, and the possibility of lateral skidding down the slope must be considered. On slopes greater than 10 degrees, down-slope skidding is a serious consideration, and the possibility of slope instability must be considered. Surface roughness superimposed on an overall slope can either increase or decrease the attitude of the foundation, depending upon how the foundation is initially emplaced. In selecting and designing a foundation, the worst situation (where large surface roughness will result in increased initial tilt) must be assumed. The larger the size of a foundation, the less significant is the surface roughness.

Most seafloor installations will be relatively inaccessible. For the case of such installations which are highly sensitive to tilting, the means to correct for detrimental inclination (or differential settlement) must be provided by including some form of leveling system between the structure and the foundation. The need for such interfacing is determined by the actual topography of the site; for the case of imperfect knowledge, it is determined by assuming the worst likely topography at the site. As shown in Appendix C, the nature and cost of the foundation system (including any required interfacing) for an installation are dependent upon the accuracy of the available topographic knowledge. In general, foundation costs may be expected to increase as the reliability of information decreases. The relationship of costs to topographic accuracy is primarily a function of the type of installation.

Bottom Currents. Ocean bottom currents may have four principal effects in relation to seafloor installations:

1. Lateral forces due to hydrodynamic drag may cause excessive soil pressures under the "downstream" side of a foundation, or may cause lateral motion of an installation.

2. The currents may create scour pits, thus undermining a foundation.

3. The currents may stir up the bottom sediments, thus reducing the visibility at a site and increasing the effective density of the fluid medium. This increase in density can result in large changes in the loads applied to a foundation by a near-neutrally buoyant structure.

4. The currents affect the accuracy with which an installation may be placed at a given site.

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The first two of these directly affect the performance of the foundation. The latter two (with the exception of the increased fluid density effect) influence construction and positioning capabilities and will be discussed in subsequent sections.

There are five major causes of bottom currents: (1) variation in the density of seawater, (2) wind drag on the ocean surface, (3) tidal forces, (4) internal waves, and (5) tsunamis.

Density currents result from the tendency of cold water to sink and displace warmer, less-dense water. The largest sources of cold water are the arctic and antarctic regions, from which the cold water spreads over the ocean floor toward the equatorial regions. Density currents are believed to be distributed throughout the oceans of the world and are considered to be the motive force of most deep-ocean circulation.

Currents induced by wind drag on the ocean surface are of two types: (1) large permanent ocean currents, and (2) secondary currents caused by transitory weather conditions or wave action. The currents of the first type are also related to the density differences in the oceans. Wind-induced currents, of either type, are primarily surface currents, because viscous friction within the water column rapidly diminishes the available energy. The maximum depth to which secondary currents are considered to be significant is about 600 feet. The permanent ocean currents, whether the result of wind drag or a density difference, may be significant at much greater depths. For example, in crossing the Blake Plateau, off Florida, the Gulf Stream has sufficient force to scour the bottom at depths of 3,600 feet and to prevent deposition of fine sediment over most of the plateau.[28]

Bottom currents due to tides can be significant to great depths. In fact, tidal flow theoretically is virtually constant from the surface to the bottom.[28] However, viscous friction and inertia effects dissipate available energy so that bottom velocities in deep water are less than surface velocities. Significant tidal effects have been reported 100 feet above the bottom in 7,400 feet of water. In shallow water, the bottom currents may be large, particularly at narrow bay entrances. For instance, Shepard[28] reports a tidal current with a velocity of 6 knots at the surface and a velocity of 3 knots 2 feet above the bottom in 100 feet of water at San Francisco Bay.

Internal waves are an oscillation of the interface of adjacent stratified water masses in the ocean. The wave action is similar in form to ordinary wind (gravity) waves, although the surface motion is negligible. Internal waves can exist in any depth of water, wherever a density stratification exists, and may result from forces such as the passage of a slowly moving ship or atmospheric pressure changes. Theoretical calculations indicate that bottom current velocities associated with internal waves may be great enough to scour bottom sediments.

Tsunamis are waves which result from major seismic or volcanic disturbances on the seafloor. The length of tsunami waves is about 100 miles, the period is about 15 minutes, and the speed of the wave front is on the order of 400 to 450 mph. The waves can travel thousands of miles with little loss of energy. In deep water, the wave height is only about 2 feet, and subsurface current velocities are less than 0.2 knot. In shallow water, the wave energy becomes concentrated, and much greater wave heights and current velocities may exist.

At a given location, the bottom current is likely to be the result of a combination of the preceding causes. Ordinarily, the causes can only be inferred from information concerning the location, depth, and topography of a site; in other words, where large tides are known to exist, it can be assumed that the primary source of bottom currents is the tidal current.

The effects of the lateral forces due to hydrodynamic drag are similar in principle to the effects of placing an installation on an inclination—the higher soil pressures under foundation elements on the "downstream" side of the structure may cause differential settlements and, perhaps, overturning. Lateral motion (skidding) may also occur. The solutions for these problems are use of low-profile installations that offer minimum resistance to current flow, widely spaced foundation elements, and greater embedment of the foundation elements or anchors.

At a site where the bottom current either is relatively constant in velocity or oscillates in a fairly regular manner, an equilibrium bottom profile is developed. The emplacement of an installation alters the flow pattern, and a new profile will develop. This new profile may involve scour pits that undermine the foundation elements. Model tests are the only practicable means of predicting the new equilibrium profile. The hazard of scour undermining may be reduced by embedment of the foundation below the probable maximum depth of scour and by designing the installation to minimize disturbance of the current flow.

Direct measurements of subsurface current velocity are scarce, and measurements made within a few feet of the bottom are rare. Often the presence of bottom currents can only be inferred from photographs of the bottom which show ripple or scour marks. The available data indicate that bottom currents of up to 0.2 knot are common (occur in 75% of the data), currents of 0.2 to 0.5 knot occur occasionally (20% of the data), and currents greater than 0.5 knot occur rarely (5% of the data). However, because most of the reported data are average values, greater peak currents evidently exist. Table 6 summarizes the probable average velocities associated with the various types of bottom currents. It appears that the minimum steady current which an installation should be designed to resist is 0.5 knot. Because larger current velocities are known to exist, direct measurement of the bottom currents at a proposed site is desirable, if not actually mandatory.

Table 6. Average Bottom Current Velocities

Current Type	Location	Velocity	Remarks
Density difference	found throughout oceans of world	<0.5 knot	Density currents are believed to be force behind most deep-ocean circulation.
Wind-generated	shallow water	small in water beyond 100 meters deep (<0.1 knot)	Wind-generated currents are confined to water less than 600 feet deep.
T _Jl currents	bays, narrows, straits	may be more than 1 knot in some cases	Tidal currents influence bottom currents to great depth.
Internal waves	found throughout world where multi-layered ocean exists	may be several tenths of a knot (<0.6 knot)	Internal waves result from oscillation of interface of two adjacent stratified water masses. Very difficult to detect from surface.
Earthquake-generated tsunamis	most found in Pacific but can occur anywhere in oceans	small in deep water (<0.2 knot); larger in shallow water (>0.2 knot)	Energy is given to seawater, which can move great distances as wa.es without loss. As water becomes shallow on approach to land, energy becomes concentrated in less and less water, producing greater ·.'ncities.

Technological Factors

Positioning. The task of placing an object on the seafloor at a given location usually consists of three separate problems: (1) establishing the surface position of the vessel relative to land, (2) maintaining surface position, and (3) establishing the position of the object on the seafloor relative to the vessel. In general, the accuracy with which an object can be placed on the seafloor is inversely proportional to both the distance from land and the water depth at the site. Appendix D lists the various systems that are available for establishing surface position and for surface-to-bottom positioning.

Within about 5 nautical miles of land, surface vessels can be positioned with an accuracy of about 5 to 15 feet by visual fixes on land with a sextant. Somewhat greater accuracy can be achieved by using more precise surveying equipment. Beyond 5 miles, some form of radio or radar navigation equipment is usually used for establishing surface position. For distances up to 200 nautical miles, accuracies of 15 to 200 feet are possible. Beyond 200 miles, the

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accuracy varies from 200 feet to 5 nautical miles, depending on the navigation system used. Virtually all of the systems are adversely affected by weather conditions or other atmospheric disturbance.

The most efficient means of maintaining surface position depends upon the water depth, the size of the vessel, the probable sea state, and the desired accuracy and duration of position holding. In shallow water, a vessel can be moored with shipboard equipment for short times. However, few vessels carry enough gear to establish a reliable mooring in water deeper than about 200 feet. Bottom mooring systems become extremely complex and expensive as the water depth, vessel size, and desired accuracy increase. Thus, they should be attempted only for long-term surface operations.

The other general method of maintaining position may be termed "dynamic positioning." In this method, a vessel is held near a suitable reference point (such as given LORAC coordinates or a seafloor acoustic beacon) by the controlled application of power to counteract wind and current drift or wave action. The power may be supplied by the vessel's own engines (including special auxiliary engines) or by auxiliary tugs for large vessels or unpowered work platforms. The control may be either manual or automatic, although manual control becomes tedious in rough seas or for long periods of station keeping.

An object lowered to the seafloor usually will not come to rest immediately below the vessel because of the effects of subsurface currents and vessel motion. This circumstance ordinarily is not detrimental for single-unit installations unless the exact geographic location must be known with great accuracy. For installations which involve the mating of several modules, some means of controlling the position of the modules is required. Table D-2, Appendix D, indicates that most of the systems which are capable of sufficient accuracy to permit mating of components without diver aid are still in the experimental stage. The only method currently available (positioning by submersible) is quite expensive.

The difficulty and expense of accurately positioning a seafloor installation have several effects upon foundation design. First, the problems involved with mating of individual units suggest that for the near future, most installations in deep water will be so designed that the foundation elements are integral with the main structure. This will increase the load-handling problems because of the increased weight of the total unit. Second, a "site" for a seafloor installation must be considered as an area with dimensions considerably larger than the plan dimensions of the installation itself. Thus, topographic surveys and soil sampling must be carried out over a wide area to determine the probable variation of the respective parameters at the site, and the foundation must be so designed that it will perform satisfactorily at any location

within the site. Finally, the difficulty of returning to a site and relocating a seafloor installation makes it imperative that the foundation be as maintenance-free as is practicable.

Load Handling. The maximum weight and size of a seafloor installation may often be limited by the available load-handling capability. In general, the lifting capacity of existing systems decreases with increasing water depth; this load–depth relationship is shown in Figure 8. Most of the data points represent salvage operations rather than emplacement of installations. Thus, the relationship shown may overestimate emplacement capability, because greater control may be required for emplacement than for salvage.
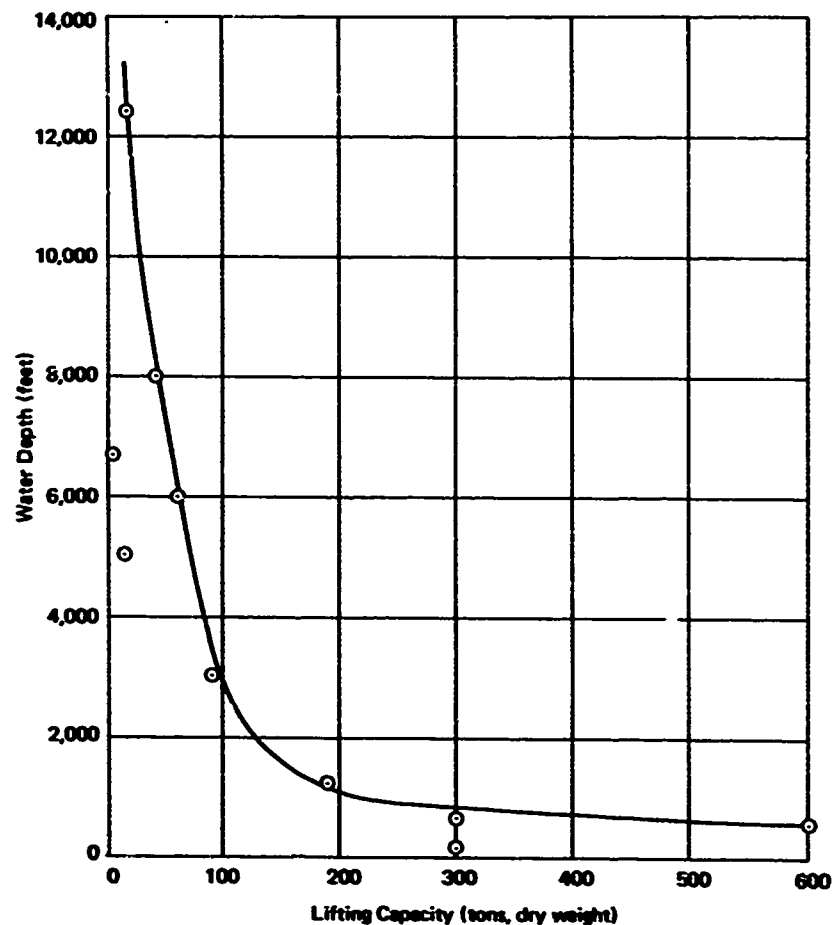
Figure 8. Lifting capacity of existing load-handling systems. (After Reference 29.)

The maximum size of an object that can be handled depends upon the type of surface vessel employed and on whether the vessel must handle the load without assistance. Surface vessels can be classified either as "ships," which have the major portion of the hull near the water surface, or as "platforms," which have a major portion of the hull considerably below the water surface.[30] Platforms generally have a centerwell of large dimensions, frequently greater than 100 feet. Ships may have centerwells or may handle the load over the side. The maximum dimension for the centerwell of a ship is on the order of 20 to 25 feet. The size of loads handled over the side of a ship may be limited by boom length or overturning moment.

The handling of an object from a surface vessel may induce large dynamic stresses in the object as well as in the load-handling system. This is particularly true if the object must be handled at, or above, the air—water interface. This circumstance has the effect of increasing the weight of the installation and of the foundation system, because the components of the structure and of the handling system must be designed to resist those dynamic loads.

Current load-handling capabilities constrain foundation design primarily by limiting the size of foundation elements that can be emplaced from unassisted vessels. For a ship with a centerwell, the maximum size of the foundation elements will be about 20 by 20 feet. The allowable bearing capacity for a footing of this size, on typical seafloor sediments, might be on the order of 50 tons. The need to limit settlement of an installation may considerably reduce the allowable load. Thus, if installations of greater weight are to be emplaced, it will be necessary to provide assistance to handle the larger foundation elements.

Construction Techniques. Construction in the ocean has been limited to depths of a few hundred feet and has usually consisted of operations performed from the surface with moderate assistance from divers. Construction, in the sense of assembling components to form an integrated structure, has not been accomplished beyond diver depths, except for certain oil well completion and connection procedures still in the development stage. Thus, the capabilities to perform construction operations on the seafloor can be categorized as either diver-assisted capabilities or unassisted capabilities.

Divers can perform a variety of construction tasks underwater but are limited in their efficiency by both physiological and physical factors. Depth and bottom-time limitations of standard compressed-air diving systems (scuba and hard-hat) can be overcome by utilizing mixed-gas and saturation diving techniques, respectively. Working dives beyond 300 feet are not unusual, although they are not yet routine; the current maximum depth capability is approximately 850 feet.

For performance of useful work, divers require suitable tools. Portable power tools are utilized whenever possible for efficiency. An extensive review of tools and equipment available for divers, and of diver work procedures, is contained in Reference 31. Virtually all of the work procedures necessary for assembly of seafloor installations from prefabricated components (such as cutting, joining, and drilling) can be performed by divers. The most difficult task is the lifting and transporting of heavy components; several systems for accomplishing this are being developed.

Installations beyond diver depths are ordinarily accomplished by the lowering of complete units which do not require any assembly activity. With few exceptions, submersibles have not been developed to perform construction activities other than site reconnaissance and inspection of installations. Several general-purpose submersibles are equipped with manipulators which can handle light tasks, but generally the submersible, the manipulator, and the various terminal devices cannot exert significant forces for lifting, transporting, or joining. Several special-purpose submersibles are being developed for the offshore oil industry for installing and maintaining seafloor wellheads; however, these lack the versatility necessary for general construction.

Underwater concrete placement is a specialized construction activity that has been proposed for use in the fabrication of seafloor installations. Several placement methods are available, as indicated in Table 7. Of the available methods, only precast concrete is suited for use in hollow, pressure-resistant structures. The other methods would be suitable for constructing such solid sections as leveling pads and foundations.

Experience has shown that fairly complex seafloor construction activities can be performed with the aid of divers, even though the diver/constructor is considerably less efficient than his land counterpart. A diver is frequently invaluable as an observer, even if he takes no direct part in the construction activity. Beyond diver depths, presently available submersibles are useful primarily for observation; considerable development is necessary before they can be used for any major construction tasks. For the near future, installations at depths inaccessible to divers will continue to be emplaced as single units. As the size of seafloor installations increases, it will be necessary to develop connecting devices which can be operated either automatically or from a submersible, so that the foundations for such installations can be emplaced separately.

Table 7. Underwater Concrete Placement Methods

Method	Maximum Known Placement Depth	Quality of Placed Concrete	Remarks
Tremie	170 feet	good; 4,000 to 6,000 psi	System consists of hopper and vertical pipe of from 2.5 to 18 inches in diameter. Provides continuous placement. Bottom of pipe must be kept immersed in the fresh concrete and must be raised during the pour with a minimum of disturbance and jerking. Extension of depth limit to 400 feet possible.
Underwater buckets	240 feet	good; 3,500 to 4,000 psi	Versatile system consisting of bottom-dump buckets which deliver freshly mixed concrete via cables. System best used for mass concrete pours, where bucket can be set on bottom. Placement not continuous.
Prepacked concrete	300 feet	good; 4,000 psi	System where coarse aggregate is placed in forms and then grout is pumped into voids, displacing water. Mix of grout very important. Complex inserts can be preplaced in deep underwater pours.
Fabriform	untried at sea	good	System consists of nylon-fabric form which is pumped full of sand—cement grout, expelling water in the process. No rigid forms required. Various shapes possible.
Bagged and sacked concrete	diver depth	fair	Bags or sacks of wet or dry concrete are lowered to seafloor for placement by divers. Strength of concrete mass may be limited by bond between sacks.
Pumped concrete	untried at sea	good	Concrete is forced through hoses into forms on seafloor. Has not been used as yet on seafloor. This system could be used either from surface or from submarine. Available pumps need to be improved for seafloor application of system.
Precast concrete	variable	excellent	Concrete members are cast at a convenient site, then transported to placement site and sunk. Careful control of mixing, curing, and sizing is possible. Tremie concrete is sometimes used to join concrete sections. Widely used system for all types of seafloor structures.

Materials. Materials used on the seafloor are subject to deterioration by chemical, electrochemical, mechanical, and biological forces. For satisfactory performance, a material should either be relatively unaffected by the hostile environment or have a predictable reaction to the various forces of deterioration. In addition, the cost, weight, strength, and compatibility with other materials must be considered to ensure that the most effective material is chosen for a given application. The materials that have been used most often, and that have been investigated most thoroughly, are concrete,[32] metals, and plastics.[33]

Portland cement concrete is frequently used in the marine environment for bridge piers, dock and wharf structures, and deadweight anchors. Most of the difficulties that have been experienced have occurred between the low tide level and the splash zone, where alternate wetting and drying may be detrimental to unprotected concrete. Where concrete is completely and permanently submerged, it is little affected by the marine environment unless it has been poorly designed or manufactured (or both). The most common causes of deterioration are abrasion by strong, coarse sediment-laden currents; attack by rock-boring marine organisms; chemical reaction between constituents of seawater and the concrete or aggregates; and corrosion of reinforcement. The detrimental effects of all of these can be minimized, if not eliminated, by employing dense, high-strength concrete. Other helpful techniques are (1) the use of hard, abrasion-resistant aggregates, (2) the use of sulfate-resisting cement and sound aggregates to resist chemical attack, and (3) the provision of sufficient concrete cover over the reinforcement to minimize corrosion.

Metals are probably the most common materials for seafloor use. The great backlog of experience and technical development in ship and submersible construction provides the major portion of the design technology necessary for efficient and economical use of metals for seafloor installations. Although serious corrosion can, and does, occur in many instances, it is usually possible to avoid difficulty by good design and proper attention to detail. Most classes of steel have relatively uniform and predictable corrosion rates and can be utilized for periods of exposure as long as 5 years by providing extra thickness to allow for corrosion or by cathodic protection and painting.[34] However, stainless steel is not recommended because of its nonuniform corrosion behavior.[35] Aluminum alloys can also be used for as long as 2 years if provided with a paint system and cathodic protection.[36] For longer periods of exposure, some nickel-base[37] and titanium[38] alloys can be used. Dissimilar

metals must be avoided or isolated from each other to prevent production of galvanic cells, which lead to serious corrosion. Coatings may also be helpful, but care must be taken not to scratch the surface, because corrosion may then occur at the scratch.

Plastics are most often used on the seafloor for such nonstructural applications as electrical insulation, rope, and coatings for metals. However, some small acoustic installations have utilized polyvinyl chloride (PVC) as the foundation element (see Figure 1). Some plastics are susceptible to biological attack by marine wood borers when the plastic is in contact with wood; some are also subject to deterioration from water absorption. Water absorption causes some plastics to soften and may lead to excessive deformations in load-carrying members.[39]

Experience and the results of extensive research show that all of the foregoing materials can be used effectively in the marine environment. The primary requirement is for sufficient attention to detail—such things as eliminating galvanic couples or providing sufficient concrete cover over reinforcement. For small, lightweight installations, rigid thermosetting plastics, such as polyvinyl chloride, are suitable for use as foundation elements. However, most seafloor installations will probably require foundations with greater strength and stiffness than is practicable with plastics alone. In this situation, the plastic can be used for the portion of the foundation which contacts the seafloor and metal can be used for the main load-carrying members. In this way, the metal is not in contact with the sediments (where corrosion rates are several times those in the water column), and nearly neutrally buoyant plastic can be used for members carrying smaller loads. Metals can be used alone in many situations where weight is to be minimized and the corrosion can be handled. Where the submerged weight of the foundation need not be minimized or where the weight is needed, concrete is a suitable material.

Summary

The foregoing review of factors which affect the choice and design of a specific foundation configuration indicates several major problem areas for seafloor foundation engineering. The problem areas, listed in approximate order of magnitude, are:

1. Minimization of stresses induced in an installation by relative movement of the points of support

2. Providing and maintaining a substantially level attitude of the installation

3. Providing adequate bearing capacity

4. Preventing collapse (overturning) due to undermining

5. Preventing lateral movement

6. Minimizing total settlement

These problems are not unique; terrestrial foundation engineering has addressed itself to these same problems for centuries. However, the magnitude of the problems is greatly amplified on the seafloor because of the environment and the status of required technological capabilities. Table 8 indicates which of the various factors (design constraints) affect the problem areas. These relationships can be summarized as follows:

1. The status of knowledge concerning the distribution and engineering properties of seafloor sediments is the most important factor controlling the capability to analyze and design foundations for seafloor installations. This is, of course, a rather obvious deduction, because the performance of a foundation depends upon the character of the underlying sediments and the accuracy and completeness with which the sediment properties have been determined.

2. The quantity and accuracy of topographic information concerning a given site significantly affect the capability to prevent relative displacement of points of support, to provide a level attitude for an installation, and to prevent lateral movement of an installation. Effects upon other problems are secondary or indirect.

3. The availability of information on bottom currents significantly affects the capability to prevent relative movement of points of support, to prevent overturning due to undermining, and to prevent lateral movement.

4. Positioning, load handling, construction techniques, and materials have only secondary or insignificant effects on all problem areas. Particularly noteworthy, however, is the fact that these four capability areas have consistently identical influences on each problem area. Analysis of this identical, secondary influence indicated that these four could be combined into a single parameter, foundation emplacement capability, which could be more easily utilized in the process of foundation selection.

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Table 8. Effect of Various Foundation Design Constraints

Foundation Design Problem Area	Foundation Design Constraint						
	Seafloor Sediments	Topography	Bottom Currents	Positioning	Load Handling	Construction Techniques	Materials
Relative movement of points of support	X[a]	X	+[b]	+	+	+	+
Level attitude	X	X	+	+	+	+	+
Adequate bearing capacity	X	+	+	+	+	+	+
Undermining	X	+	X	+	+	+	+
Lateral movement	X	X	+	+	+	+	+
Total settlement	X	O[c]	O	+	+	+	+

[a] X = State of knowledge or capability has primary effect upon solution of problem.

[b] + = Secondary effect.

[c] O = Insignificant effect.

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The range of the parameter foundation emplacement capability, along with those of the previously discussed foundation design constraints, is indicated in Table 9 under the heading Foundation Systems. Each value within the range of one of these design constraints represents a possible existing condition or available capability. For an individual installation, the project engineer would have knowledge of these conditions and capabilities (or value of design constraints) for his particular installation site. This knowledge, together with information concerning the foundation requirement parameters (discussed under FUTURE SEAFLOOR INSTALLATION REQUIREMENTS) makes possible the selection of the appropriate type of foundation system (such as single spread footing or multiple-pile foundation).

In the process of selecting practical foundation systems for the seafloor it is necessary to consider all likely combinations of design constraints and foundation design parameters. Table 9 indicates all possible combinations. In the next section, the most practical foundation system for each of these combinations is determined, and the most likely combinations or situations are further discussed.

FOUNDATION SYSTEM CONCEPTS

The summary at the end of the previous section lists several generalized problem areas that confront seafloor foundation engineering. It should be emphasized that these problem areas have been stated in very broad terms, and that similar problems have been encountered (and in a general sense, solved) in the practice of terrestrial foundation engineering. Thus, terrestrial experience can suggest basic concepts for practical seafloor foundation systems. Several circumstances, however, often make direct application of such terrestrial concepts difficult. First, some of the concepts may require positioning, mapping, and construction capabilities not readily available on the seafloor. Second, certain concepts have been employed rather infrequently, so that accumulated experience is still an imperfect guide. Finally, a single concept may provide only a partial solution in a given situation, and little experience is available concerning the interaction of combined concepts. Since it appears likely that the exigencies of the seafloor environment will frequently dictate the use of uncommon foundation concepts and/or configurations, it is desirable to select a number of practical concepts and to sufficiently develop each concept so that selection and preliminary design are possible without further research. To accomplish this, it has been necessary to consider the applicability of the concepts suggested by prior terrestrial and marine experience as well as to generate new concepts which will most efficiently satisfy the foundation requirements of foreseeable Navy seafloor installations and design constraints (as indicated in Table 9). In this section, these concepts are briefly described according to their function and probable configuration, and the relative significance of each is determined.

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Table 9. Possible Combinations of Foundation Design

Foundation Requirement Classes[a]	Seafloor Sediments				Topography						
	Cohesive Soils		Sands	Rock	Overall Slope (deg)						
					0 to 1		1 to 4		4 to 10		
	Weak and Compressible	Competent			Surface Roughness						
					Small	Large	Small	Large	Small	Large	
A											
B											
C											
D											
E											
F											
G											
H											
J											
K											

[a] Defined in Table 4.

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...ns of Foundation Design Constraints and Requirement Classes

Foundation Systems									
graphy				Bottom Currents		Foundation Emplacement Capability			
Slope (deg)									
4 to 10		>10		<0.5 Knot	>0.5 Knot	Lightweight Single Module	Heavyweight Single Module	Multimodule	Seafloor Construction
Roughness									
Small	Large	Small	Large						

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Description

Foundations are often described as comprising two broad groups, shallow and deep. Shallow foundations are usually established at an embedment depth, D_f, which is less than the minimum lateral dimension, B, of a given foundation element (that is, a spread footing or mat). Such foundations essentially derive their support from the soil located less than a distance B' beneath the installation, where B' is the minimum overall lateral dimension of the total installation (see Figure 9). The depth of embedment of deep foundations is much greater than B; also, the ratio D_f/B' is commonly greater than 5. Deep foundations are considered to derive a major portion of their support from strata located greater than a distance B' beneath the installation. Shallow and deep foundations thus differ considerably in the methods employed to determine bearing capacity, as well as in construction techniques. Virtually all foundation concepts and configurations can be readily classified as either shallow or deep. Thus, the specific concepts and configurations considered are grouped under the general categories for discussion.

Shallow Foundations

The simplest form of foundation is the single spread footing or mat, which usually consists of only a flat plate resting on, or just beneath, the soil surface. The footing distributes concentrated loads applied to its upper surface over a larger soil bearing area. If the installation applies several concentrated loads (such as column loads) to the foundation, and they are spaced rather far apart, it may be more economical to provide a foundation consisting of several spread footings, each supporting a single load. This results primarily from the difficulty of handling large objects in the ocean, rather than from material costs. Multiple spread footings may also be required if the total load of the installation is greater than the allowable bearing capacity of the largest single footing practicable.

Footing and mat foundations have several features that make them very attractive for use on the seafloor, particularly (1) the relative ease of installation, and (2) the availability of fairly dependable rational design procedures. In many cases, the footings can be designed to be physically integral with the installation, thus allowing a single emplacement operation. If the footing(s) must be emplaced separately from the installation, emplacement may often be possible with only a minimum of preparation of the seafloor surface. Available data indicate that design procedures used for terrestrial foundations are applicable, at least in principle, to design of shallow-water foundations.[27] In some shallow-water cases and in virtually all deep-water applications, empirically derived constants and/or equations may require modification to account for differences in the soil properties.

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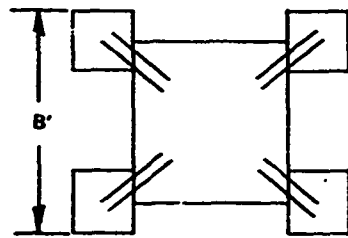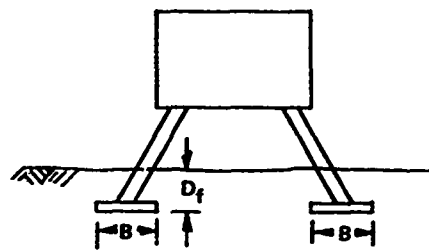
a. Spread footing foundation.
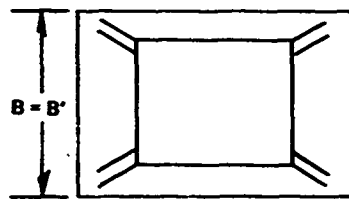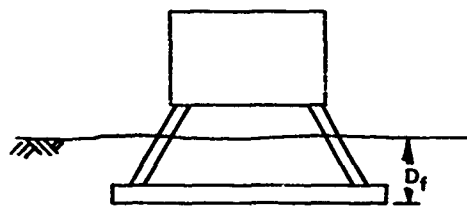
b. Mat foundation.
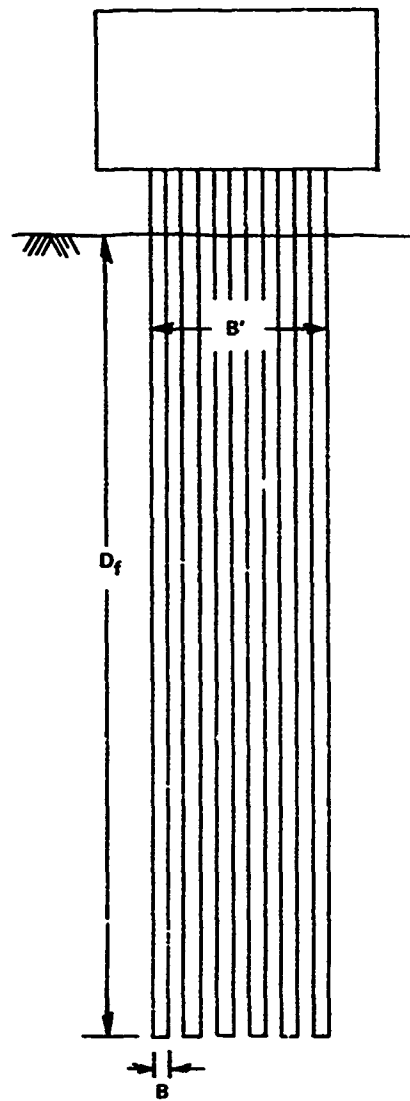
c. Pile foundation.

Figure 9. Shallow versus deep foundations.

The advantages of footing and mat foundations are somewhat offset by their susceptibility to settlement, particularly since seafloor sediments near the water—sediment interface can often be rather highly compressible. It should be possible to design most seafloor installations to accommodate a substantial amount of uniform settlement; that is, settlement not involving relative motion of the points of support. It is also probable that many installations will not be overly sensitive to relative movement of the points of support so long as the support points remain in the same plane (such as the tilting of a rigid mat). However, these are idealized cases; most real situations will involve differential settlements of the points of support, particularly with multiple-footing foundations. In general, differential settlements are undesirable, since they cause tilting of the structure and can, in some situations, induce secondary stresses within the installation.

Other likely causes of relative displacement of the points of support include irregular topography and undermining. Simple footing foundations are also occasionally susceptible to lateral motion caused by bottom currents or sloping topography. Because it appears that a significant number of seafloor installations will be sensitive to such relative displacements, it is necessary to develop foundation systems other than simple and multiple spread footings and mat foundations. It may also be practicable to slightly modify the properties of the soil or the topography in order to reduce the possibility of detrimental relative movements of the support points of the installation. One group of such foundation systems and auxiliary methods is based on the general principles of shallow foundations, and includes the following concepts: (1) weight-compensated (floating) foundations, (2) penetrating foundations, (3) precompression of the soil, (4) shape-conforming foundations, (5) variably loaded foundations, (6) protection against undermining, (7) protection against skidding, and (8) site excavation.

Weight-Compensated Foundations. Weight-compensated, or floating, foundations are occasionally employed in terrestrial foundation practice to minimize total and differential settlements of a structure, or to minimize shearing stresses in the soil. Essentially, the concept consists of constructing the foundation so that it displaces an amount of soil equal in weight to the total weight of the structure. In this manner, the stress in the soil beneath the foundation is unchanged, at least theoretically, and no settlement should occur. In principle, the soil need possess no shear strength at all; that is, the structure and its foundation could be floated like a ship.

In practice, the most common use of the concept is in the utilization of deep basements to reduce the stresses under a heavy building. It is not typical to entirely eliminate stress increases beneath the foundation. The costs of excavation, and of providing basement walls strong enough to withstand the high earth pressures, are often too great. In the ocean environment,

the concept is not significantly different from that of using either inherent or added buoyancy to reduce the net load on the seafloor—an approach which is very common. The weight-compensated foundation could consist of a rigid box of either metal or concrete. Although it would be possible to allow the installation simply to settle until it reached equilibrium, it is desirable that the sediment be excavated to the required depth to allow more positive control of the state of stress in the sediment.

Penetrating Foundations. Since the strength of seafloor sediments can be expected to increase rapidly with depth in the first few feet, it may often be advantageous to establish the foundation slightly below the water—sediment interface to take advantage of the higher bearing capacity. The extremely high compressibility of these surficial sediments also makes it desirable to penetrate several feet. In addition, the burial of the foundation elements can be useful as a means of providing lateral resistance, or to mitigate the effects of scour. Once again, this technique is typically employed in terrestrial foundations. However, the technique is usually implemented by excavating the soil to the level of the foundation. Excavation of the seafloor, discussed in detail in a subsequent section, in water of more than moderate depth, will be difficult and expensive. In very soft sediments, it may not be possible to hold an excavation open, and in any case it will be difficult to position an installation within an excavation. Thus, it is desirable to consider foundations that will penetrate through the weak upper layers and thus require no excavation of the site. The primary force behind the penetration could be the inertia of the installation as it is lowered to the seafloor. (Note that a weight-compensated foundation that is allowed to sink of its own weight could be classified as a penetrating foundation.) It may be desirable to utilize water jets beneath the foundation to aid in displacing the sediments. One suggested approach would utilize a water-filled bag attached to the underside of the foundation. As this bag would begin to penetrate the seafloor and push some of the softer sediments aside, it would burst and the released water would tend to wash additional sediment out of the way. This concept and a more conventional approach are illustrated in Figure 10.

Precompression of the Soil. This general concept may be applied in two distinct cases: (1) where the site is underlain by compressible cohesive soils, and (2) where the site is underlain by loose cohesionless soils. Settlement of a structure that must be constructed over a compressible cohesive soil may be minimized by causing the soil to consolidate prior to construction. This has been accomplished on land either by preloading the soil with a surcharge or by inducing drainage of the pore water with sand drains. The process

must be initiated considerably in advance of construction in order to allow time for the pore water to drain from the soil. The process ordinarily has the added advantage of increasing the shearing strength of the soil, thus permitting a foundation with a smaller bearing area. At the end of the precompression period, the surcharge is removed and the structure is built. The length of the precompression period, and the amount of surcharge required, depend upon the degree of consolidation desired, and the characteristics of the soil, particularly the coefficient of consolidation which controls the rate at which consolidation occurs.

On the seafloor, this concept might be applied in two ways: (1) by the preceding process of preloading with a surcharge, or (2) by inducing an effective surcharge on the soil by applying a negative relative pressure to the pore water in the soil. In effect, the second method would utilize a portion of the weight of the water column above the soil as a surcharge. The precompression of a large area by the second technique would require a separate power source for pumping. For individual or multiple footings of moderate size, this appears to be fairly simple to accomplish.

Figure 11 illustrates schematically how a preconsolidating footing would look; Figure 12 shows a model preconsolidating footing used in laboratory-scale investigations of this concept.

Results of a typical short-term load test of two identical 7-inch-diameter footings, one subjected to a preconsolidation pressure of 5 psi for 3 days, are shown in Figure 13. These data illustrate the two distinct attributes of preconsolidation of a site: (1) the increase in the ultimate bearing capacity (in this case from approximately 130 to 190 psf); and (2) the decrease in the amount of settlement which will occur at allowable bearing pressures (virtually zero immediate settlement at a bearing pressure of 60 psf on the preconsolidating footing, and 0.1 inch immediate settlement at a pressure of 40 psf for the simple footing). These settlements are immediate or plastic settlements rather than long-term settlements attributable to primary consolidation or secondary compression; however, the magnitude of immediate settlement can be taken as an indication of the expected relative magnitude of long-term settlement.

The use of a physical surcharge as required in the preloading concept for accomplishing precompression is somewhat limited by the requirement to provide a preload greater than the structure weight and then to remove the surcharge when the precompression is complete. A concept utilizing this technique is illustrated in Figure 14. This particular concept has the additional advantage of using the preload weights as surcharge subsequent to the pre-loading phase, thus increasing the bearing capacity of the foundation.

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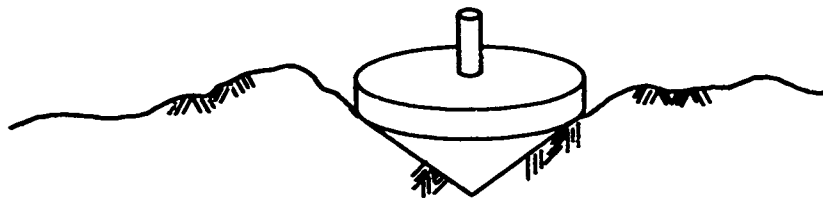
a. A simple penetrating footing.
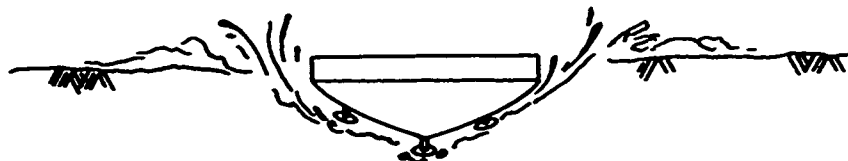
b. Water jet assisted penetration.
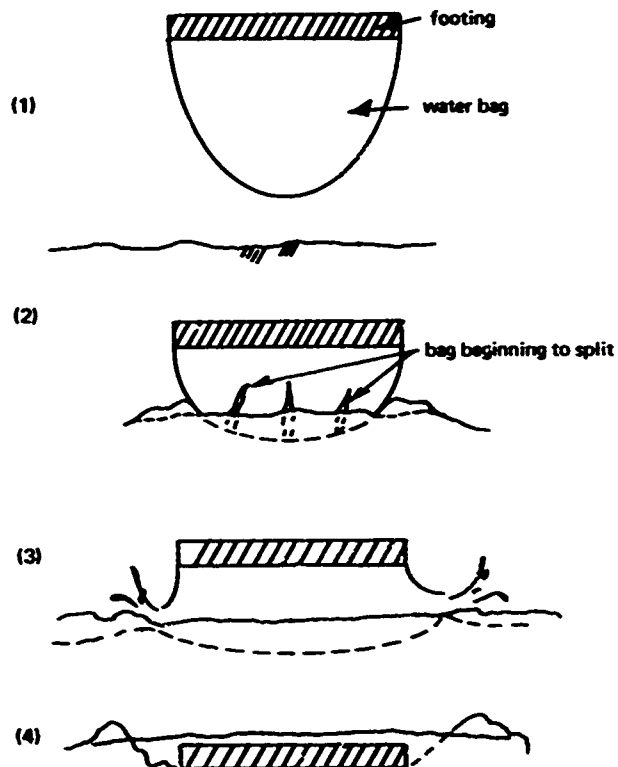
c. Water bag penetrating footing.
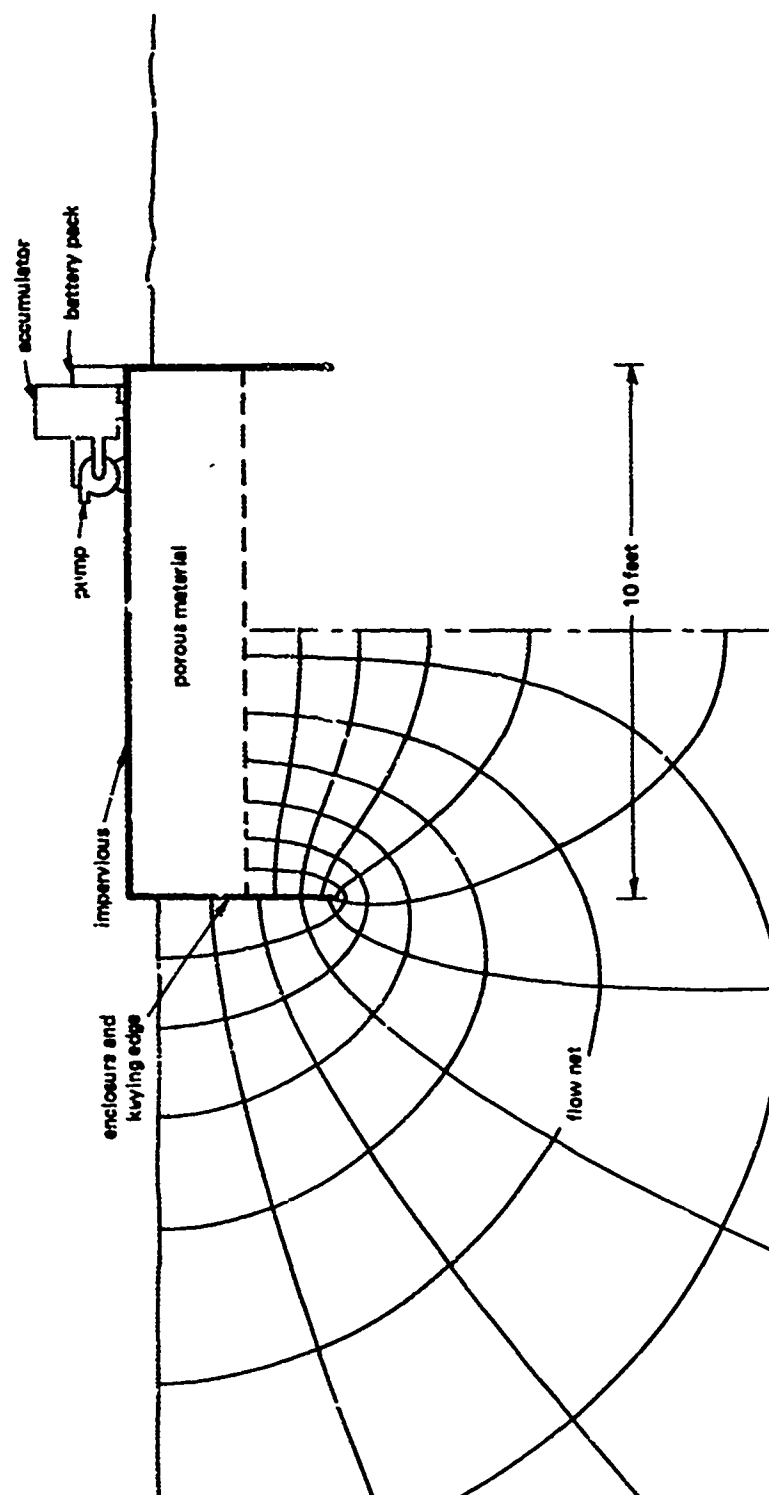
Figure 10. Penetrating foundations.

Figure 11. Schematic of preconsolidating footing.

labels within figure:
accumulator
battery pack
pump
porous material
impervious
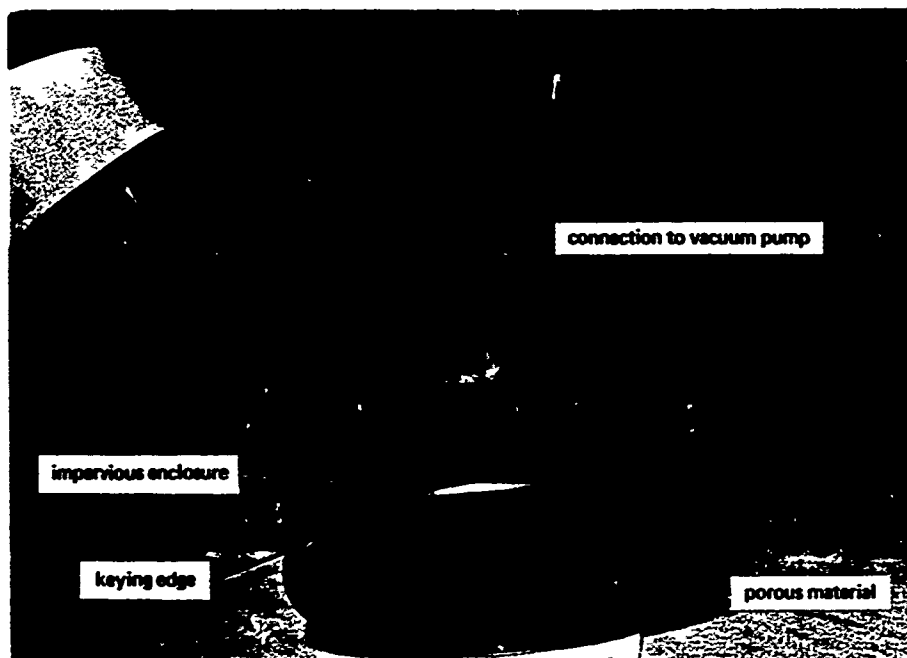enclosure and keying edge
flow net
10 feet
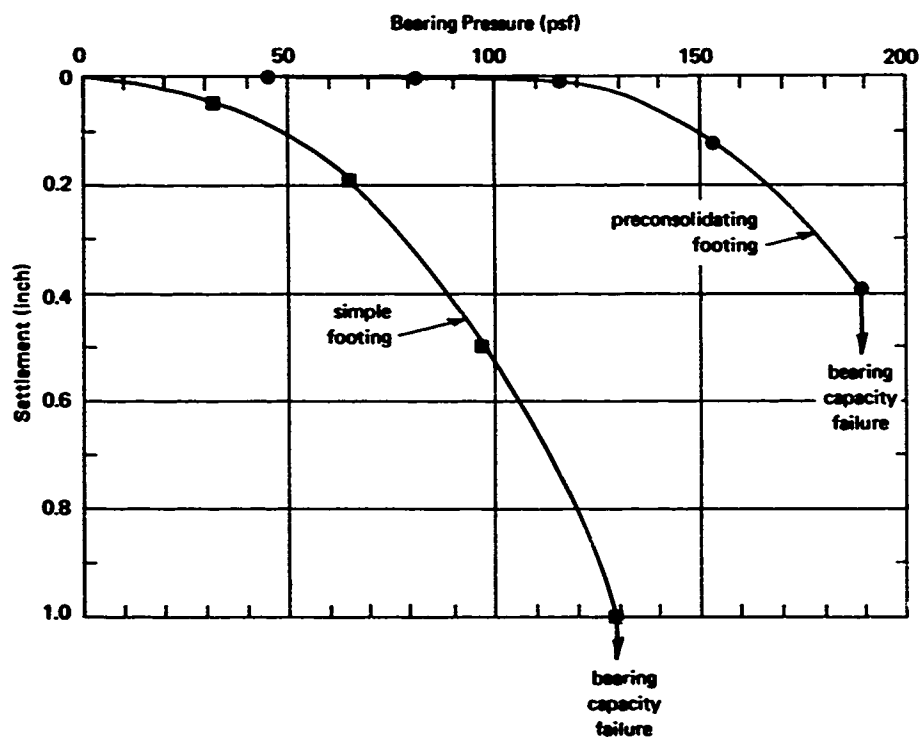
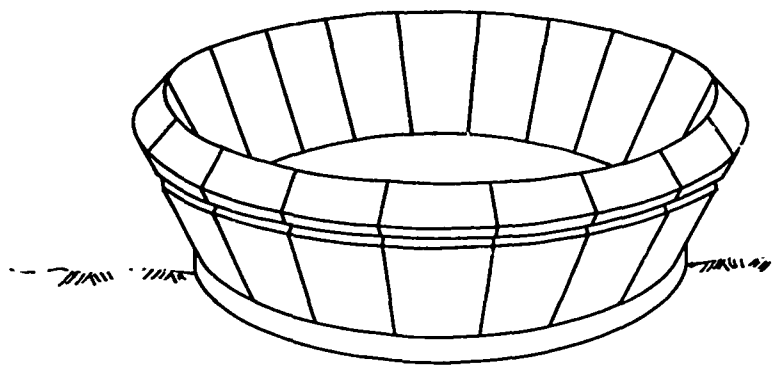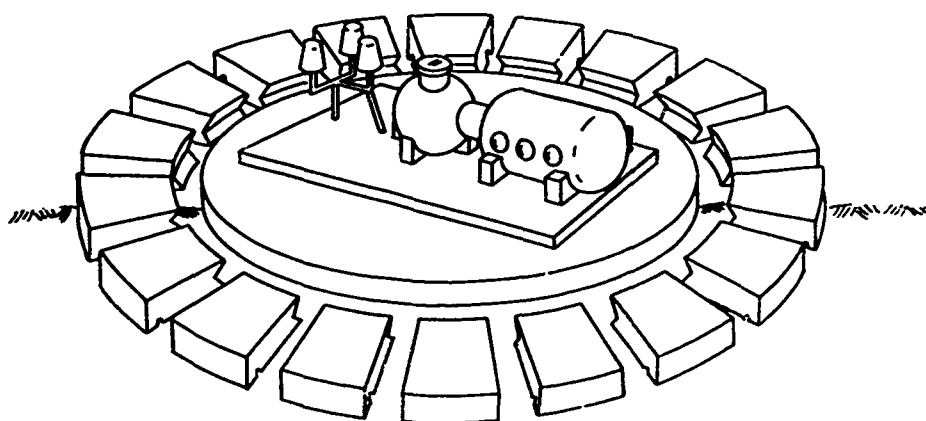Figure 12. Model preconsolidating footing.

Figure 13. Load—settlement curves for two model footings.

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a. During preloading phase.

b. After preloading phase with preload acting as surcharge.

Figure 14. Preloading foundation.

It may occasionally be necessary to compact loose deposits of cohesionless soils in order to increase stability and prevent large settlements due to vibration of the installation or due to shock (blast or earthquake) loadings. This can be accomplished by vibrating the soil prior to construction. In some situations it may be possible through the use of explosives to effect densification through shock loading.

Shape-Conforming Foundations. For the near future, most seafloor installations are expected to occupy relatively shallow-water sites in positions on the continental shelves and slopes, midocean ridges, and seamounts. These sites will occasionally present problems for the flat-plate spread footing or mat because irregular topography or rock outcrop may be encountered. The use of such footings on rock surfaces would require highly overdesigned bearing elements. Similar use on irregular-surfaced weak soils could lead to undesirable local bearing-capacity failures.

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Several techniques could be used in these two situations to provide a means of conforming to the seafloor surface. A footing could be cast in place (using a material such as concrete) or the space beneath a rigid footing could be filled with some material such as grout to give continuous contact. A specially designed prefabricated spread footing might be used to accomplish very nearly the same effect and would be more useful in deep water. The bottom of the foundation would be provided with a thick layer of crushable material. When emplaced upon a very irregular, hard surface, the crushable material would collapse at points of high bearing stress, thus transferring load to other contact areas until a nearly uniform bearing stress condition is reached. On weak soils exhibiting irregular topography, the same purpose can be accomplished by the use of multiple articulated spread footings arranged in a triangular or other determinate pattern. (Such a configuration is illustrated in Figure 15.)

Variably Loaded Foundations. For most structures located on cohesive seafloor soils, the foundation design is more heavily influenced by considerations of settlement than by the limitations imposed by bearing capacity. In designing to minimize differential settlement one approach is to decrease the bearing pressure where excessive local settlement is occurring. The most direct method of accomplishing this on the seafloor is to increase the bearing area and thus decrease the applied stress. By using shallow cone-shaped or slightly curved (dish-shaped and concave upward) footings, the area of contact of an individual spread footing can be increased as settlement or penetration into the seafloor occurs. In this manner, further settlement at that footing will be slowed by the decrease in bearing pressure. The same approach can be used with footings of other shapes, such as square and strip footings.

Such a footing configuration would be slightly awkward in appearance and might seem to be an uneconomical use of possible bearing area. This concept can be applied, however, where a seafloor structure cannot tolerate differential settlement or tilting, and this is the main constraint in foundation design.

Another concept utilizing a variable loading technique involves the embedment of a keying edge. In this situation, the objective is proper foundation installation rather than minimization of differential settlement. Several foundation concepts described in subsequent sections require such a keying edge. The force required for proper embedment can be rather large and is sensitive to any variation in soil properties. In most cases, the depth and thickness of the edge will be selected on the basis of the soil properties at the site. At many locations, the proper evaluation of these properties would be expensive and in some cases extremely difficult. In this situation, a standard keying

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edge mounted on the perimeter of a flexible footing (typically circular) could be used, and a detailed evaluation of soil properties forgone. The flexibility of the footing would be designed to apply up to three-quarters of the entire load on the footing to the keying edge. If the edge does not completely embed under this load (because of strong soil), the flexibility of the footing allows the edge to deform to such an extent that the footing will still bear upon the soil over the center of its area. Thus, the footing could be used on soils ranging from weak and compressible to more competent, and precise data on the soil properties at the site would not be required.
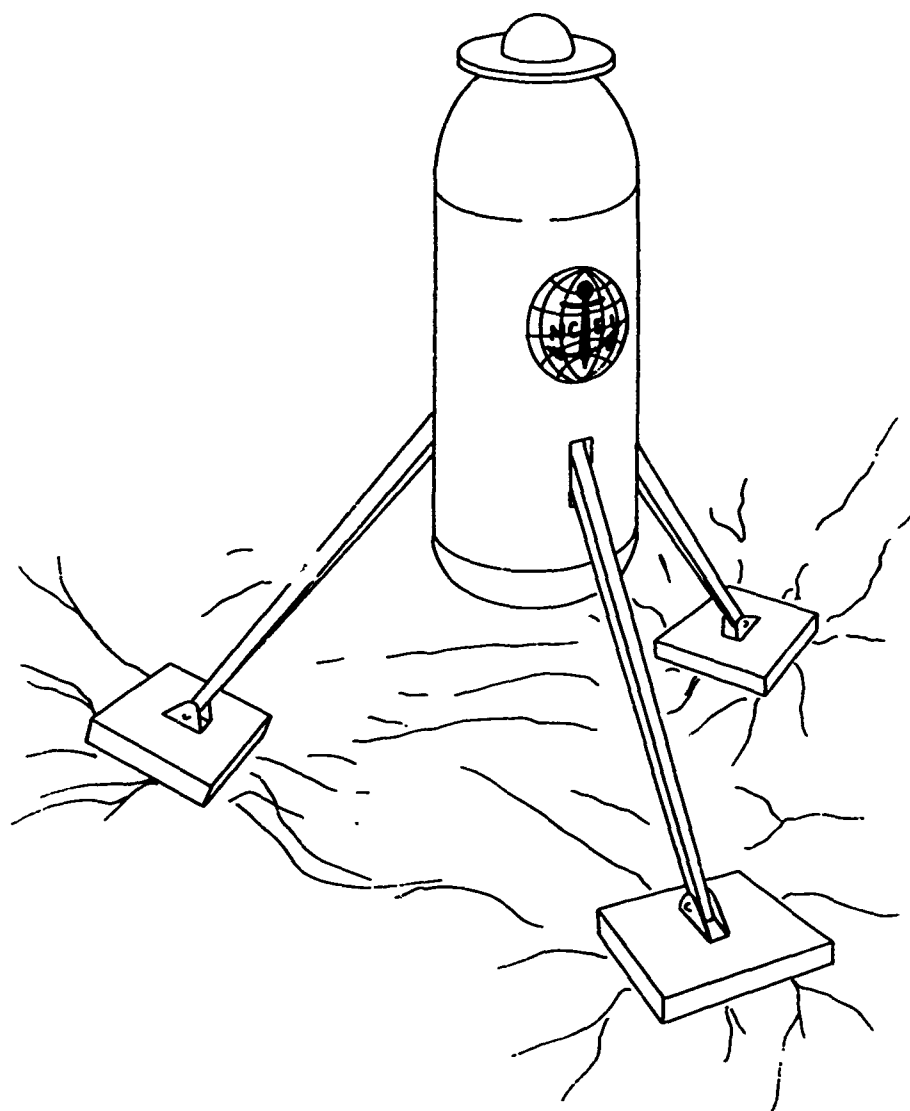

Figure 15. Tripodal arrangement of articulated spread footings.

Protection Against Undermining. Experience with seafloor structures has shown that undermining due to the scouring action of bottom currents and surge, and to biological activity (such as undermining by crabs and fish) can lead to failure of the foundation.[40] One foundation concept which minimizes this effect is a low-profile, streamlined, spread footing with a perimeter cutting edge. The low and streamlined profile reduces disturbance to natural flow patterns. This disturbance or turbulence causes the scouring. The embedded perimeter edge forms a mechanical barrier to prevent the loss of material from beneath the footing. This cutting edge also aids in the prevention of such biological activity as animal undermining. Enclosing the soil completely on top and on all sides with a relatively impervious material (such as concrete, metal, or plastic) prevents oxygen from getting to the soil, and thus creates an anaerobic environment toxic to almost all living forms. The perimeter edge also acts as a mechanical barrier to any burrowing animals which might undermine a footing.

Protection Against Skidding. There have been at least two known instances where a simple spread footing has skidded down a gentle slope, or started to do so.[1] One means of preventing such movement is the use of keys on the underside of the footing. These mechanical projections are designed to key the footing into the deeper soils, which have more strength and resistance to lateral motion. Several variations of this keying concept are possible. For granular soils, these keys may be relatively small and located under the center of the footing, where proper embedment can be more easily effected. For cohesive soils, a larger key is typically required. The simplest solution in this case is a perimeter keying edge which has the additional capabilities described under the preceding section.

Protection against skidding may be very critical on a rock bottom, because such a surface is likely to be irregular and/or sloping. In this case, the mechanical projections would probably take the form of short (stubby) piles with sharpened points. These would be designed either to penetrate the rock surface or to lodge in irregularities in the rock surface in order to provide lateral resistance. The lateral resistance would be enhanced by designing the "piles" to project somewhat outward, rather than directly perpendicular to the foundation. Also, the overall stability would be enhanced if the piles were arranged in a tripodal or otherwise determinate pattern (Figure 16).

Site Excavation. Shallow foundations are either embedded slightly into the seafloor or located at the seafloor surface. The former requires a means of accomplishing the embedment. One approach is on-site excavation of material.

For a structure with a foundation located at the seafloor surface, the existing topography can have a significant effect upon the performance of a foundation. A foundation deployed on a slope is subject to additional tilting

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as a result of differential loading and settlement. The differential loading increases the possibility of local bearing capacity failures. Such a foundation can also be subject to lateral skidding if initial inclination is sufficiently steep and proper protection, as described in the preceding section, is not provided.
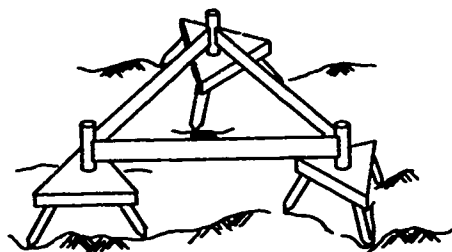

Figure 16. Multiple stubby pile configuration.

Problems resulting from initial inclination can be reduced if the site is leveled prior to emplacement of the foundation. Site leveling can be accomplished in several ways, including site excavation.

Excavation can be accomplished by several mechanical concepts, such as those shown in Figure 17. Typically, a rather complex device and control system would be required at all except the shallower sites where divers could accomplish the work. Excavation at a site for purposes of either foundation embedment or site leveling would typically improve foundation performance. However, consideration must be given to the possibility of mass instability of the excavated site and of the soil which is removed.

Deep Foundations

Deep foundations are utilized where the upper layers of soil are too weak or compressible to execute a satisfactory spread foundation, and thus the structure loads must be transferred to more suitable soil at greater depth. Deep foundations may also be employed to eliminate the effects of scour, to provide lateral stability to the foundation, and to provide uplift resistance.

Deep foundations are usually classified as piles, piers, or caissons. The classifications are commonly based upon the method of installation and perhaps the relative size (length-to-diameter ratio) of a given foundation element. For the present purpose, piles will be defined as deep foundation elements emplaced primarily by driving, vibrating, or jacking, with soil excavated only to assist penetration. Piers and caissons are deep foundation elements emplaced primarily by excavation of soil, followed by in-place construction of the member (ordinarily by concreting). With a single exception, construction methods for piers or caissons will be limited to relatively shallow water (on the order of 300 feet). The only method whereby soil can be excavated to a significant depth

in the soil profile in relatively deep water is the use of marine oil-drilling techniques and equipment. Thus, the following discussion will be confined to piles, with the understanding that drilled-in piers are included.

Types of Piles. Piles are ordinarily classified as friction piles or point-bearing piles. Friction piles transfer most of the applied load by friction and adhesion between the soil and the side of the pile. Point-bearing piles transfer most of the applied load to a firm stratum at the tip of the pile. The analysis and design criteria are significantly different for the two idealized cases, and the choice of type depends upon the soil profile. Ordinarily, point-bearing piles are preferred, because the analysis and design procedures are more reliable than for friction piles. Friction piles are utilized where a firm bearing stratum cannot be reached economically, which is anticipated to be the typical situation on the seafloor.

Pile Foundations. Terrestrial pile foundations usually utilize at least three piles in a group to support column loads; it is quite common for pile groups to contain many more than three piles. However, it is anticipated that it will be desirable to emplace a minimum of piles for a seafloor foundation to minimize disturbance to the soil and to minimize installation costs. Thus, a foundation consisting of a single pile will be an attractive solution in many cases, particularly for compact installations of moderate weight which require rather high reliability. Installations of large size and/or weight will require multiple-pile foundations for sufficient load capacity and stability. However, the emphasis will still be on utilizing the minimum practicable number of piles. Thus, the spacing between piles will be considerably greater than is common on land, and analysis and design procedures will be somewhat different, because terrestrial procedures take into account significant interaction among piles in a group. These differences are not likely to require radical changes in design approach. However, the most significant drawback to pile foundations is the lack of an emplacement method for deep-water applications. Exploratory research and development is being conducted to develop a seafloor pile emplacement system, and it is anticipated that this drawback can be eliminated in the relatively near future.

Structure—Foundation Interfacing System

Terrestrial structures are typically attached rigidly to their foundations. This may not be the most desirable situation on the seafloor for three reasons: (1) the sites for most seafloor foundations will not be prepared (compacted or excavated), thus the entire soil profile and its naturally occurring properties must be utilized in the design; (2) existing topography is a rough and uneven foundation base by terrestrial standards but must be accommodated by the foundation design; and (3) differential settlements will typically be much larger for seafloor conditions.
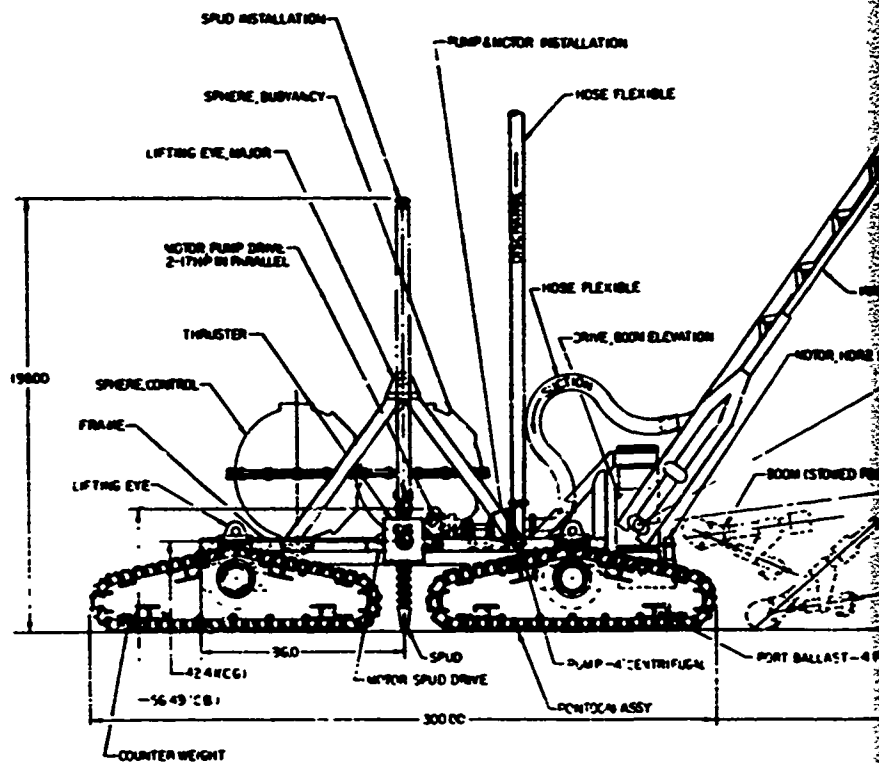
a. Mobile excavator.

Figure 17. Concepts for site excavators. (A

60A
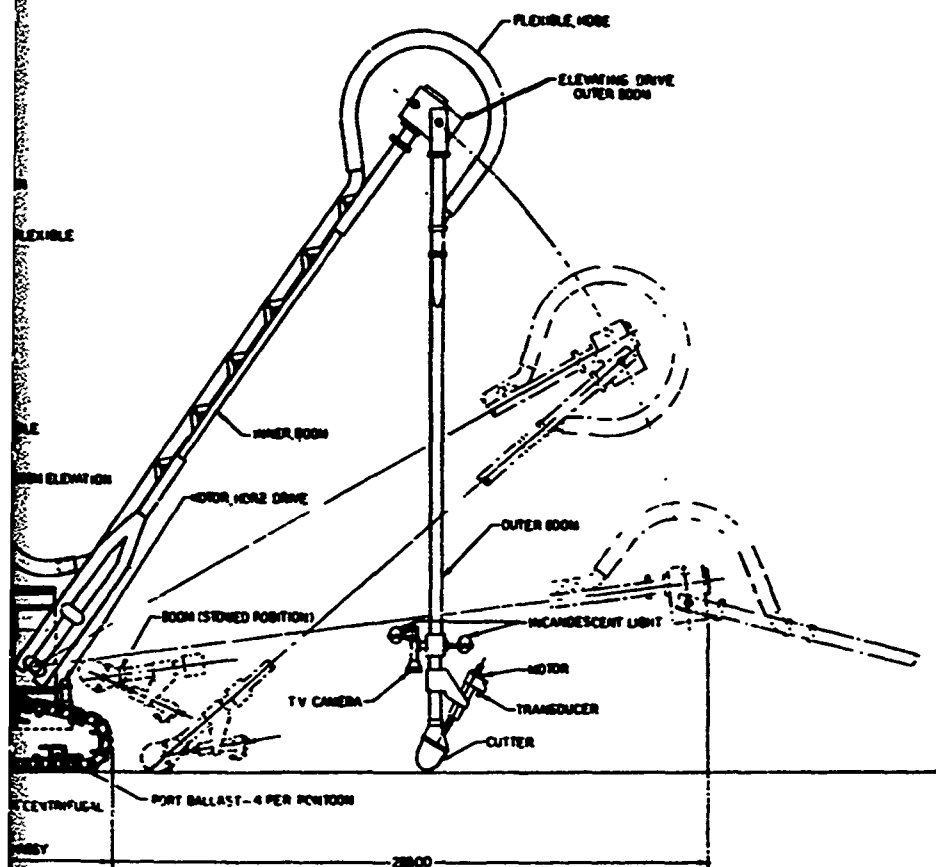
a. Mobile excavator.

...ts for site excavators. (After Reference 41.)

5 1/2 IN. DRILL PIPE

DISCHARGE ORIFICE

SPOILS HOSE

POWER AND
CONTROL CABLE

CUTTER HEAD

UMBILICAL

ANCHOR PILE

b. Unipile.

c. Resolver excavator.

Figure 17. Continued

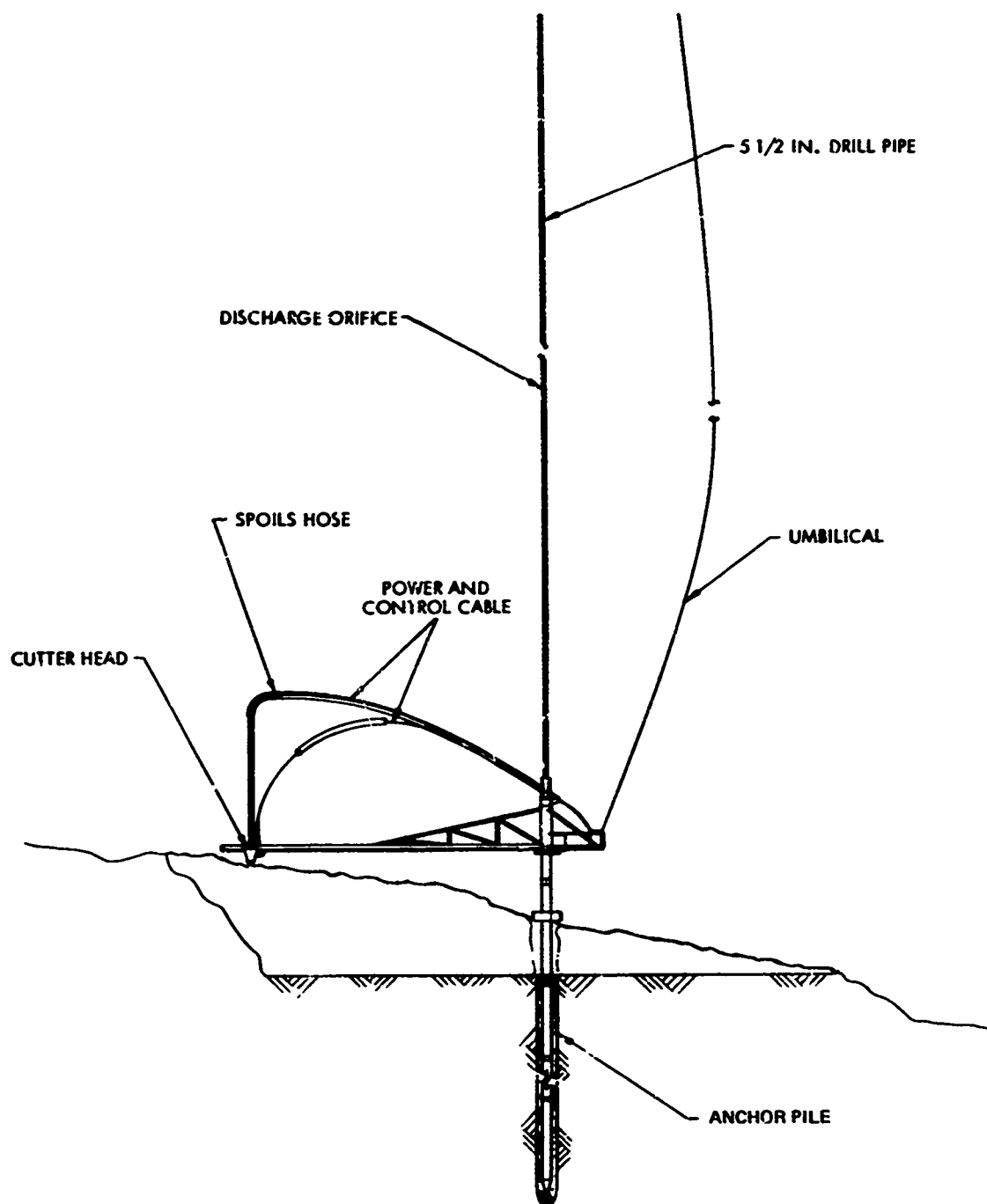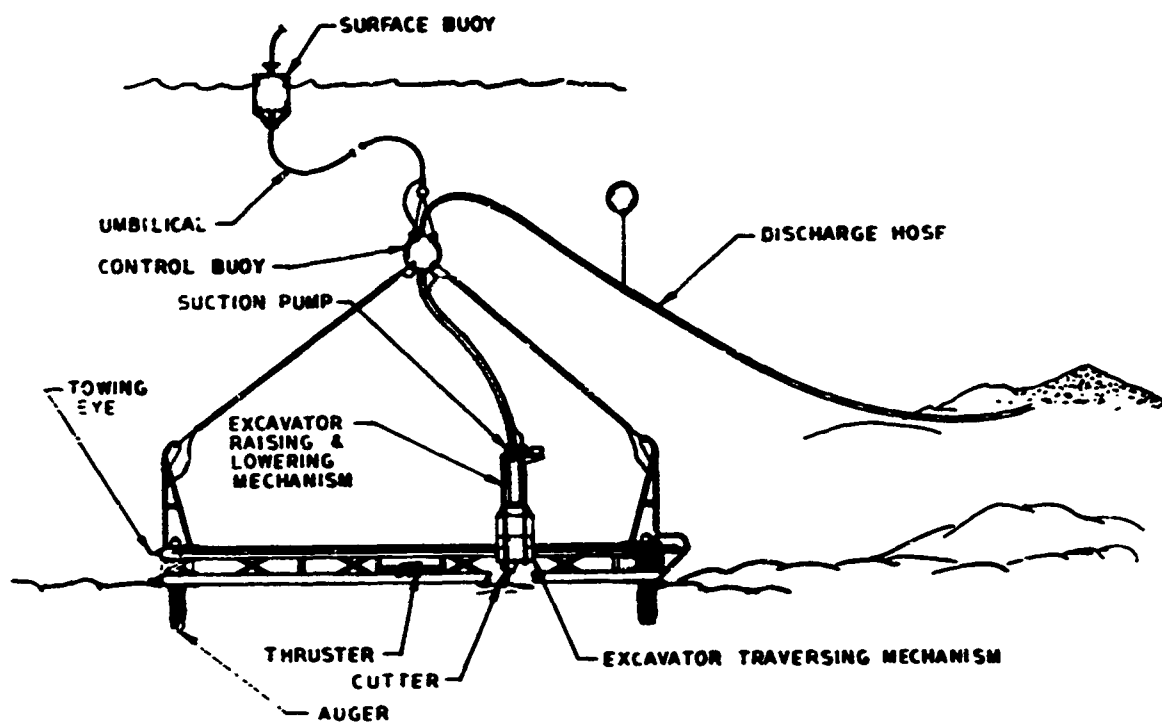For the many seafloor structures which will be sensitive to tilting and differential settlement and for larger structures requiring numerous foundation elements, or points of support, some type of interfacing system may be required. Such a system would be designed to level a structure deployed on irregular or sloping topography, distribute the loads of a structure to the various points of support on a foundation system, and maintain a structure in a level attitude as foundation elements are subjected to settlement, possibly differentially, over time.

Such a system could be made up of a series of jacks (mechanical or hydraulic) which would be individually activated to adjust load or elevation relative to the foundation element. Such a system could be used in conjunction with any type of foundation configuration including multiple piles, multiple spread footings, large mat foundations, and others.

Selection of Foundation Systems

The preceding portion of this section has listed and discussed a number of types of possible foundation systems. This list included several terrestrial foundation systems which appear applicable, or have been used, in the seafloor environment. A number of other concepts for seafloor foundation systems were also listed. These were based on ideas suggested directly by others or indirectly by their work, or generated as a result of the investigation summarized in this report. Some of these are concepts for a complete foundation system; others are only a component of a total system. These components are usually designed to help in one situation or to handle one particular type of problem. When combined with other components or added to other concepts, these give a total foundation system.

Each system, or collection of components making up a system, has a particular set of characteristics which determine the situations (combinations of foundation requirements and foundation design constraints, see Table 9) for which it is best suited. For example, a single spread footing with a keying edge is best suited for installations of small size and weight requiring resistance to lateral motion or protection from undermining by animals or current scouring action. Thus, it is particularly well adapted for sites on gentle slopes and in regions exhibiting moderate currents or biological activity. A review of all concepts and combinations giving total foundation systems showed that altogether there are 21 unique practical foundation concepts among which all possible situations could be handled. These are listed in Table 10.

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Table 10. Practical Foundation Concepts

Symbol	Foundation Description
SS	Simple spread footing
SSU	Keyed spread footing
SSN	Preconsolidating spread footing
SSD	Preloaded spread footing
SSK	Variably loaded spread footing
SSY	Shape-conforming or yielding spread footing
SSP	Penetrating spread footing
MS	Multiple simple spread footing
MSTA	Tripodal arrangement of articulated SSU's
MSN	MSTA configuration using SSN's
MSTY	MSTA configuration using SSY's
MSP	MS configuration using SSP's
PS	Single-pile foundation
PMQ	Multiple-pile foundation
PMR	Multiple stubby pile foundation
MF	Mat foundation
MFWE	Weight-compensated mat foundation
MFE	Mat foundation on preleveled site
MFC	Cast-in-place mat foundation
MFG	Undergrouted mat foundation
Prefix L	Structure—foundation interfacing system

One of the objectives of the study summarized in this report was the determination of the foundation system concepts which would be the most practical, from the standpoint of satisfying foreseeable Navy needs for seafloor structures and accommodating the design constraints imposed by likely site characteristics. Table 9 indicates all possible combinations of foundation requirement classes (foreseeable Navy needs) and foundation design constraints (both environmental and technological). For each of these possible situations the practical foundation concept which best satisfied the requirements and constraints was determined. The concepts selected for each of the situations are shown in Table 11.

Table 11. Selected Practical Foundatio

(For definitions of systems refer to Tabl

Foundation Requirement Classes	Seafloor Sediments				Topography						Foundation Syst
	Cohesive Soils		Sands	Rock	Overall Slope (deg)						
					0 to 1		1 to 4		4 to 10		
					Surface Roughness						
	Weak and Compressible	Competent			Small	Large	Small	Large	Small	Large	Sm
A	SSU	SS	SS	SSY	SS	SS	SS	SSU	SSU	PS	P
B	MSTA	MSTA	MSTA	PMR	MSTA	MSTA	MSTA	MSTA	MSTA	MSTA	P
C	MF	MF	MSTA	MSTY	MF	MF	MF	MSTA	MSTA	MSTA	PN
D	MSP	MSTA	MSTA	MSTY	MSN	MSN	MSN	MSN	MSN	PS	P
E	MSN	MSN	PMQ	PMR	MSN	MSN	MSN	MSN	MSN	PMQ	PN
F	MF	MF		MSTY	MF	MFG	MF	MFG	PMO	PMO	PN
G	MFWE	MSN	A	MSTY	MSN	MSN	MSN	MSN	PS	PS	P
H	PMQ	PMQ	MF	PMR	MF	MFG	LMF	LMFG	PMO	PMO	PN
J	LMSN	LMSTA	LMSTA	LPMR	MSN	MSN	LMSN	LMSN	PMO	PMO	PN
K	PMQ	PMQ	MFE	LPMR	MF	MFG	PMO	PMO	PMO	PMO	PN

lected Practical Foundation Systems

itions of systems refer to Table 10.)

Foundation Systems									
phy				Bottom Currents		Foundation Emplacement Capability			
pe (deg)									
4 to 10		>10		<0.5 Knot	>0.5 Knot	Lightweight Single Module	Heavyweight Single Module	Multimodule	Seafloor Construction
ughness									
Small	Large	Small	Large						
SSU	PS	PS	PS	SS	SSU	SS	SS	PS	PS
MSTA	MSTA	PS	PS	MSTA	PS	MSTA	MSTA	PS	PS
MST'	MSTA	PMQ	PMQ	MF	MF	MSTA	MF	PMQ	MFC
MSN	PS	PS	PS	MSN	MSN	MSTA	MSTA	MSN	MSN
MSN	PMQ	PMQ	PMQ	MSN	PMQ	MSTA	MSTA	MSN	PMQ
PMQ	PMQ	PMQ	PMQ	MF	MF	MF	MF	PMQ	PMQ
PS	FS	PS	PS	MSTA	MSN	MSTA	MSTA	MSN	MSN
PMQ	PMQ	PMQ	PMQ	PMQ	PMQ	MF	MF	PMQ	PMQ
PMQ	': PMQ	PMQ	PMQ	LMSN	PMQ	LMSTA	LMSN	LMSN	PMQ
PMQ	PMQ	PMQ	PMQ	LMF	PMQ	LMF	LMF	PMQ	PMQ

Table 12. Situations Most Likely to Occur and Systems

(For definitions of systems refer to Tab

Foundation Syst

Foundation Requirement Classes	Seafloor Sediments				Topography						
	Cohesive Soils		Sands	Rock	Overall Slope (deg)						
					0 to 1		1 to 4		4 to 10		
	Weak and Compressible	Competent			Surface Roughness						
					Small	Large	Small	Large	Small	Large	Sm
A	SSU	SS	SS	SSY	SS	SS	SS	SSU	SSU	PS	P
B	MSTA	MSTA	MSTA	PMR	MSTA	MSTA	MSTA	MSTA	MSTA	MSTA	P
C	MF	MF	MSTA	MSTY	MF	MF	MF	MSTA	MSTA	MSTA	PM
D	MSP	MSTA	MSTA	MSTY	MSN	MSN	MSN	MSN	MSN	PS	P
E	MSN	MSN	PMO	PMR	MSN	MSN	MSN	MSN	MSN	PMO	PM
F	MF	MF	MF	MSTY	MF	MFG	MF	MFG	PMO	PMO	PM
G	MFWE	MSN	MSTA	MSTY	MSN	MSN	MSN	MSN	PS	PS	PS
H	PMO	PMO	MF	PMR	MF	MFG	LMF	LMFG	PMO	PMO	PM
J	LMSN	LMSTA	LMSTA	LPMR	MSN	MSN	LMSN	LMSN	PMO	PMO	PM
K	PMO	PMO	MFE	LPMR	MF	MFG	PMO	PMO	PMO	PMO	PM

65A

…or definitions of systems refer to Table 10.)

Foundation Systems										
Topography					Bottom Currents		Foundation Emplacement Capability			
Overall Slope (deg)										
	4 to 10		>10		<0.5 Knot	>0.5 Knot	Lightweight Single Module	Heavyweight Single Module	Multimodule	Seafloor Construction
Surface Roughness										
…ge	Small	Large	Small	Large						
SU	SSU	PS	PS	PS	SS	SSU	SS	SS	PS	PS
STA	MSTA	MSTA	PS	PS	MSTA	PS	MSTA	MSTA	PS	PS
TA	MSTA	MSTA	PMO	PMO	MF	MF	MSTA	MF	PMO	MFC
SN	MSN	PS	PS	PS	MSN	MSN	MSTA	MSTA	MSN	MSN
SN	MSN	PMO	PMO	PMO	MSN	PMO	MSTA	MSTA	MSN	PMO
FG	PMO	PMO	PMO	PMO	MF	MF	MF	MF	PMO	PMO
SN	PS	PS	PS	PS	MSTA	MSN	MSTA	MSTA	MSN	MSN
FG	PMO	PMO	PMO	PMO	PMO	PMO	MF	MF	PMO	PMO
SN	PMO	PMO	PMO	PMO	LMSN	PMO	LMSTA	LMSN	LMSN	PMO
MO	PMO	PMO	PMO	PMO	LMF	PMO	LMF	LMF	PMO	PMO

Of the 21 concepts listed in Table 10, only 15 were determined to be required to satisfy all of the possible situations shown on Table 11. It is also indicated by this table that of these 15 some are required in a larger number of situations than others. Another consideration which must be made is the fact that all of these situations are not equally likely. Table 3 indicates that there is a larger predicted need for future foundations in Foundation Requirement Classes A, D, and G. Class J is also a more immediate need because it includes the requirements representative of the first manned installations. Similarly, not all possible variations of each design constraint are equally likely, in fact the likely limiting design constraints are somewhat related to the foundation requirement class. This is because foundations in each class typically have similar missions. These missions typically determine location, and design constraints are primarily a function of location and site conditions.

Table 12 indicates the combinations of foundation requirement classes and likely design constraints expected to occur most often in the foreseeable future. A summary of the practical foundation concepts providing the best solution for each of these situations indicates that 11 systems are required. These 11 candidate foundation systems are discussed in the next section.

RESULTS AND DISCUSSION

Foundation Selection

In the preceding sections, a systematic procedure, illustrated in Figure 18 as a flow chart, has been used to select 11 candidate practical foundations. To accomplish this, foreseeable Navy needs for seafloor installations have been summarized according to installation categories (Table 1). The foundation performance criteria for these installations were defined in terms of foundation requirement parameters useful for foundation analysis and design. These parameters include reliability, sensitivity to tilting, weight, and size; they are summarized for each installation category in Table 2. By considering only the most likely, or most critical, combinations of foundation requirement parameters, the foundation needs for foreseeable Navy installations can be categorized into 10 foundation requirement classes (Table 4). The influence of environmental conditions (such as soil type, macrotopography and microtopography, and bottom currents), and the limitations imposed by existing technological capabilities (such as load handling, positioning, and seafloor construction capability), have been summarized in terms of foundation design constraints (Table 9). The requirement classes and design constraints were systematically combined into situations, for each of which a practical

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foundation solution could be selected (Table 9). Possible foundation system concepts and configurations were analyzed, and a group of 21 practical foundation concepts was selected (Table 10). The probable performance characteristics of each of the practical concepts were compared to the performance requirements of each of the situations (Table 9). By considering only those situations likely to occur in the near future, the number of concepts to be emphasized for development was reduced to 11 (Table 12). These 11 concepts are the candidate foundation systems, among which all foreseeable near-term requirements can be satisfied under expected design constraints. Table 13 lists the 11 candidate systems, and summarizes the general characteristics of each system. Conceptual designs or configurations for several of these candidates are presented in Appendix E. Estimates of performance for each of these proposed configurations under one or more sets of design constraints also are summarized in Appendix E. These give an idea of the foundation behavior that might be expected on the seafloor.
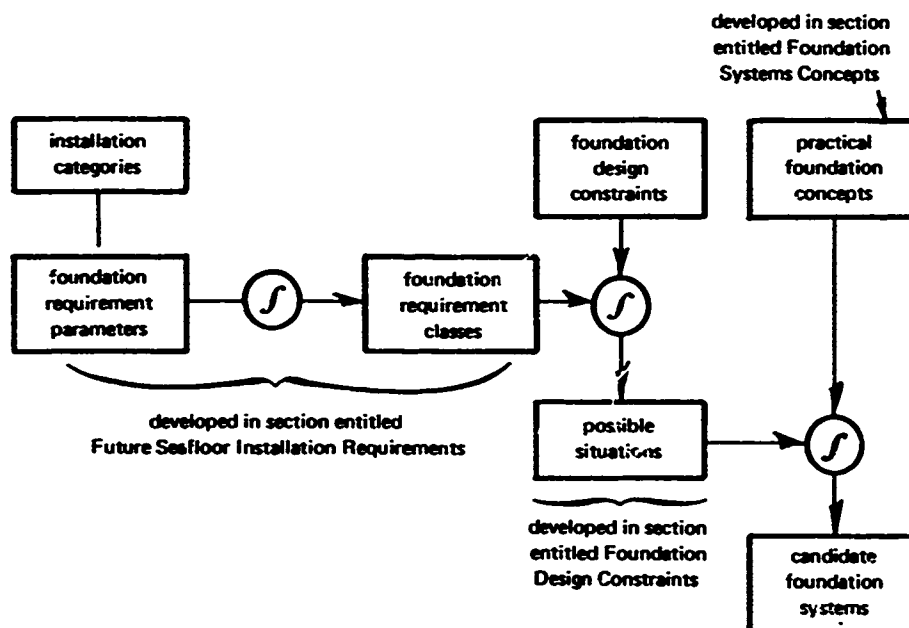
Figure 18. Systematic procedure for selection of candidate practical foundation systems.

Table 13. Candidate Foundation Systems and Their Characteristics

Foundation System	Uses	Reliability	Maximum Tilt (deg)	Vertical Load Capacity (lb)	Mean Lateral Dimension (ft)	Seafloor Type	Maximum Topographic Slope (deg)	Required Emplacement Capability
Simple spread footing (SS)	small instruments and sensors	0.9	20	4,000	12	competent cohesive, sand	4	lightweight, single module
Keyed spread footing (SSU)	small instruments and sensors	0.9	20	4,000	12	competent cohesive, sand	10	lightweight, single module
Multiple penetrating footing (MSP)	large instrumented installations	0.9	5	40,000	40	weak and compressible cohesive	10°	heavyweight, single module
Tripodal arrangement of articulated keyed spread footings (MSTA)	large instrumented installations, equipment test facilities, and manned installations	0.9 to 0.999	5 to 1	40,000	>40	competent cohesive, sand	10°	heavyweight, single module
Tripodal arrangement of articulated yielding footings (MSTY)	large instrumented installations and equipment test facilities	0.9 to 0.999	5 to 1	40,000	40	rock	10°	heavyweight single module
Tripodal arrangement of articulated preconsolidating spread footings (MSN)	large instrumented installations, equipment test facilities, and manned installations	0.9 to 0.999	5 to 1	40,000	>40	weak and compressible, competent	10°	multimodule

Table 13. Continued

Foundation System	Uses	Reliability	Maximum Tilt (deg)	Vertical Load Capacity (lb)	Mean Lateral Dimension (ft)	Seafloor Type	Maximum Topographic Slope (deg)	Required Emplacement Capability
Weight-compensated mat foundation (MFWE)	large instrumented installations and equipment test facilities	0.99	5	40,000	40	weak and compressible	4°	seafloor construction
Single-pile foundation (PS)	large instrumented installations and equipment test facilities	0.9 to 0.99	5 to 7	40,000	40	weak and compressible, sand	20°	multimodule
Multiple-pile foundation (PMQ)	manned installations	0.999	1	40,000	>40	competent cohesive, sand	20°	multimodule
Multiple stubby pile foundation (PMR)	manned installations	0.999	1	40,000	>40	rock	10°	heavyweight, single module
Structure—foundation interfacing system (prefix L)	manned installations	0.999	1	40,000	>40	competent cohesive, rock	20°	—

* Where the maximum topography: slope exceeds the maximum tilt, a means of initial leveling must be incorporated in the foundation system.

Table 13. Continued

Foundation System	Uses	Reliability	Maximum Tilt (deg)	Vertical Load Capacity (lb)	Mean Lateral Dimension (ft)	Seafloor Type	Maximum Topographic Slope (deg)	Required Emplacement Capability
Weight-compensated mat foundation (MFWE)	large instrumented installations and equipment test facilities	0.99	5	40,000	40	weak and compressible	4°	seafloor construction
Single-pile foundation (PS)	large instrumented installations and equipment test facilities	0.9 to 0.99	5 to 1	40,000	40	weak and compressible, sand	20°	multimodule
Multiple-pile foundation (PMQ)	manned installations	0.999	1	40,000	>40	competent cohesive, sand	20°	multimodule
Multiple stubby pile foundation (PMR)	manned installations	0.999	1	40,000	>40	rock	10°	heavyweight, single module
Structure–foundation interfacing system (prefix L)	manned installations	0.999	1	40,000	>40	competent cohesive, rock	20°	—

* Where the maximum topographic slope exceeds the maximum tilt, a means of initial leveling must be incorporated in the foundation system.

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Examples

The systematic procedure outlined above, and presented in Figure 18, can be used to select the appropriate foundation configuration for an individual seafloor installation, where sufficient data concerning the installation and the proposed site exist, or can be reasonably assumed. The following three hypothetical examples illustrate the procedure.

Example—Instrumented Test Stand. A test stand designed to expose material samples to the environment, and to monitor several environmental parameters such as temperature, salinity, and current, is to be deployed for 1 year in the Pacific Ocean at a water depth of 12,000 feet. This installation, similar to the one shown in Figure 2, is to be 10 by 12 by 10 feet high and weigh 3,000 pounds in water. This information can be used to determine the foundation requirement class for this installation as follows: (a) this is an unmanned, nonstrategic installation and thus probably requires only moderate reliability (0.9 as defined in Table 2); (b) none of the instrumentation is sensitive to tilting, thus it would be classed as having low sensitivity; (c) its weight is small (less than 2 tons submerged); and (d) its size is small (mean lateral dimensions of less than 12 feet). From Table 3 it can be seen that these values of the four requirement parameters define Foundation Requirement Class A.

The available data on the proposed site indicate: (a) the soil is weak and compressible cohesive soil (undrained strength less than 1 psi at a soil depth of 1 foot); (b) the overall slope, or macro topography (determined from mapping the area), is less than 1 degree, and the surface roughness (ascertained from bottom photographs) is small; and (c) the observed bottom currents are less than 0.5 knot. The emplacement procedure involves simply lowering and releasing the installation with the foundation attached. This capability (lightweight, single module) is limited primarily by the water depth. Taking these four design constraints and referring to Table 11 for Foundation Requirement Class A, one obtains the four suggested practical foundation concepts SSU (keyed spread footing, see Table 10 for definitions), SS (simple spread footing), SS, and SS, respectively. Because the SSU determination is more restrictive than the SS, it is the necessary selection for this installation. (An example of a keyed spread footing configuration is shown in Figure E-2, in Appendix E.)

Example—Rigid Acoustic Array. The second example is an installation with maximum dimensions of 15 by 25 by 20 feet high, which contains a directional, rigid acoustic array. This open-framed structure weighs 12 tons submerged and is to be placed on top of a seamount in 3,000 feet of water.

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The foundation requirement parameters can be determined, by referring to Table 2, as follows: (a) this could be a fairly strategic installation, thus the required reliability is high (0.99); (b) because it is directional, its sensitivity to tilt is high (cannot tolerate more than 1-degree tilt); (c) the submerged weight is medium (between 2 and 20 tons); and (d) the size is medium (mean lateral dimension between 12 and 40 feet). Table 3 indicates that Foundation Requirement Class H satisfies the need.

With respect to design constraints, bottom photographs of the intended site indicate the surface material to be sound rock which is very irregular on a local scale (microtopography). Topographic mapping of the area with a bottom sounder indicates the overall slope (macrotopography) to average 7 degrees. Maximum bottom currents are estimated to be large (greater than 0.5 knot). Because of the water depth, typical sea states at the site, and a possible interest in covert emplacement, a heavyweight, single module emplacement capability is the maximum available. The following determinations can be made from Table 11 for a Foundation Requirement Class H: (a) for a seafloor sediment type of rock, a PMR (multiple stubby pile foundation, from Table 10) is recommended; (b) for the topography (4- to 10-degree overall slope and large surface roughness) a PMQ (multiple pile foundation) is recommended; (c) large bottom currents suggest a PMQ again; and (d) the foundation emplacement capability suggests a MF (mat foundation). More important, the foundation emplacement capability excludes the PMQ, which requires a capability to stay on site and carry out multimodule assembly or seafloor construction. In this case a PMR (multiple stubby pile foundation, such as the one shown in Figure 16) would be the overall selection, because it can be emplaced with the structure as a single module. Because this installation must be within 1 degree of level and the overall slope averages 7 degrees, a structure—foundation interfacing system would be necessary. An initial leveling capability is all that is required of the system in this case, because only negligible long-term differential settlement would be expected on sound rock.

Example—Manned Habitat. The third example is a manned habitat. Because man-rating of the foundation is necessary, reliability must be very high (0.999). Similarly, tilting greater than 1 degree is noticeable to men, and as the tilt increases above this value their concern, and resulting work inefficiency, tends to increase. Therefore, sensitivity is rated as high. The submerged weight of the installation, when ballasted down on the seafloor, is to be 50,000 pounds, which classifies its weight as large. The maximum lateral dimensions of the installation are 40 by 80 feet, thus the size is large. Table 3 indicates that Foundation Requirement Class K fits these characteristics.

The proposed site for this installation is to be on a coral sand in 850 feet of water at a relatively protected location. The seafloor is relatively smooth (small surface roughness) and has a gentle slope of 2 degrees. Maximum bottom currents are slightly greater than 0.5 knot. Divers will be working at the site, and because both sea states and equipment availability will be favorable, a capability for seafloor construction will exist. For these four foundation design constraints, the respective suggested foundation configurations for Class K are MFE (mat foundation on preleveled site), PMQ (multiple pile foundation), PMQ, and PMQ. In this case, the constraints requiring the PMQ are more restrictive than the one suggesting MFE, thus the selected foundation configuration for this example situation would be a multiple pile foundation. (An example of this configuration is shown in Figure E-7, in Appendix E.)

CONCLUSIONS

In the processes of collecting data for this study and carrying out the systematic foundation analysis, the following conclusions were reached.

1. Analysis of available information indicates that the Navy has an increasing need for seafloor installations requiring foundation support. This increase is in terms of total number of future installations as well as in terms of their size, weight, complexity, and importance.

2. To select or design a foundation, it is necessary that the requirements for the foundation be defined quantitatively in terms of the appropriate parameters, including required reliability and sensitivity of an installation to tilting.

3. The selection and design of a foundation system are heavily influenced by the environmental and technological design constraints. Those having the largest influence include sediment type, topography, and emplacement capability. The latter constraint currently imposes a serious limitation on both the size and weight of seafloor installations and foundation systems

4. The increasing number and diversity of requirements for future Navy installations, and the variety of environmental and technological conditions under which they will be emplaced, are resulting in a general diversification of foundation needs, which will require a variety of foundation systems to satisfy these needs.

5. Foundation systems can be projected which will satisfy all foreseeable requirements and combinations of design constraints.

6. The 11 candidate foundation systems listed in Table 13 will satisfy all foreseeable near-term Navy needs. Some of these systems require additional development.

7. A systematic approach s ch as that utilized in these analyses of foundation classes, design constraints, and candidate foundations is an absolute necessity in handling foundation design information properly.

8. This systematic approach can be utilized in the design procedure for actual individual installation foundations. Its value in such an application can be increased by keeping the analysis as quantitative as is consistent with available data.

Appendix A

DISTRIBUTION AND ENGINEERING PROPERTIES OF
SEAFLOOR SEDIMENTS

INTRODUCTION

The bulk of available information concerning seafloor sediments has been obtained by marine geologists and oceanographers. Thus, much of the published information is useful only for determining the geographical distribution of generalized sediment types; not for determining engineering properties. Certain correlations between sediment type and the engineering properties of the sediment are available and are discussed below. However, it will be helpful to describe briefly the usual method of sediment classification used by marine geologists and to define certain terms that are commonly used in the literature.

CLASSIFICATION OF SEAFLOOR SEDIMENTS

Marine geologists ordinarily classify sediments primarily on the basis of grain size and secondarily on the origin or composition of the sediment particles. The most common grain size scale is the Wentworth Scale (Table A-1).

Table A-1. Wentworth Scale of Grain Size

Note: 1,000 microns = 1 millimeter

Classification	Grain Diameter (microns)
gravel	>2,000
sand	2,000 to 62.5
silt	62.5 to 3.9
clay	<3.9

The U.S. Navy Oceanographic Office uses the same scale, except that the division between silt and clay is placed at 2 microns. The sediment is classified according to the predominant grain size; if more than one grain size is present, combination terms (such as silty sand) are derived from a triangular classification chart (Figure A-1). (It should be noted that the silt and clay fractions of a sediment are frequently referred to simply as "mud.") Superimposed upon the textural classification system is a less systematic set of descriptive terms based on the origin or composition of the sediment particles. Sediment particles are referred to as terrigenic when derived from material eroded from the continents; as organic or biogenic when derived from the skeletal remains of marine plants and animals; and as authigenic when precipitated from minerals in seawater. Organic particles are further classified as calcareous when derived from organisms whose shells or skeletons consist of calcium carbonate (coral, globigerina, pteropods, etc.), and as siliceous when derived from skeletons made of silica (diatoms and radiolaria). A silt or clay sediment ("mud") containing more than 30% by volume of organic particles is called an ooze. Other index properties useful for engineering classification, such as the plasticity characteristics, or engineering properties, such as shear strength and compressibility, are usually not reported in data published before about 1960. More recent investigations frequently report such data because of the increased interest in ocean engineering and because of the usefulness of certain engineering data in evaluating the depositional history of seafloor sediments.

DISTRIBUTION OF SEDIMENT TYPES

The general distribution of sediment types on the seafloor is shown in Figure A-2. This map was compiled from several sources and indicates only the predominant sediment types in the upper few feet of the seafloor. Local anomalies exist which cannot be plotted on such a small-scale map. Table A-2 shows the percentage of the seafloor covered by the major sediment types.

The distribution of seafloor sediments is related in a general way to the topography of the seafloor. The most common sediments of the deep-ocean basins (beyond the continental rise) are calcareous oozes and "red clay." "Red clay" is an inorganic clay derived from atmospheric dust, from fine-grained terrigenic sediments that have been transported great distances by ocean currents, and to a minor extent from meteorites and volcanic dust. (The term "red clay" is unfortunate, because deep-ocean clays are most often brown. The term "brown clay" is becoming more common in recent literature.) Other deep-ocean sediments include siliceous oozes, authigenic sediments

such as manganese nodules and phillipsite, and a few terrigenic sand layers probably deposited by turbidity currents. The predominant sediment of the continental rises is terrigenic silt, which differs from the deep-ocean brown clay primarily in grain size.
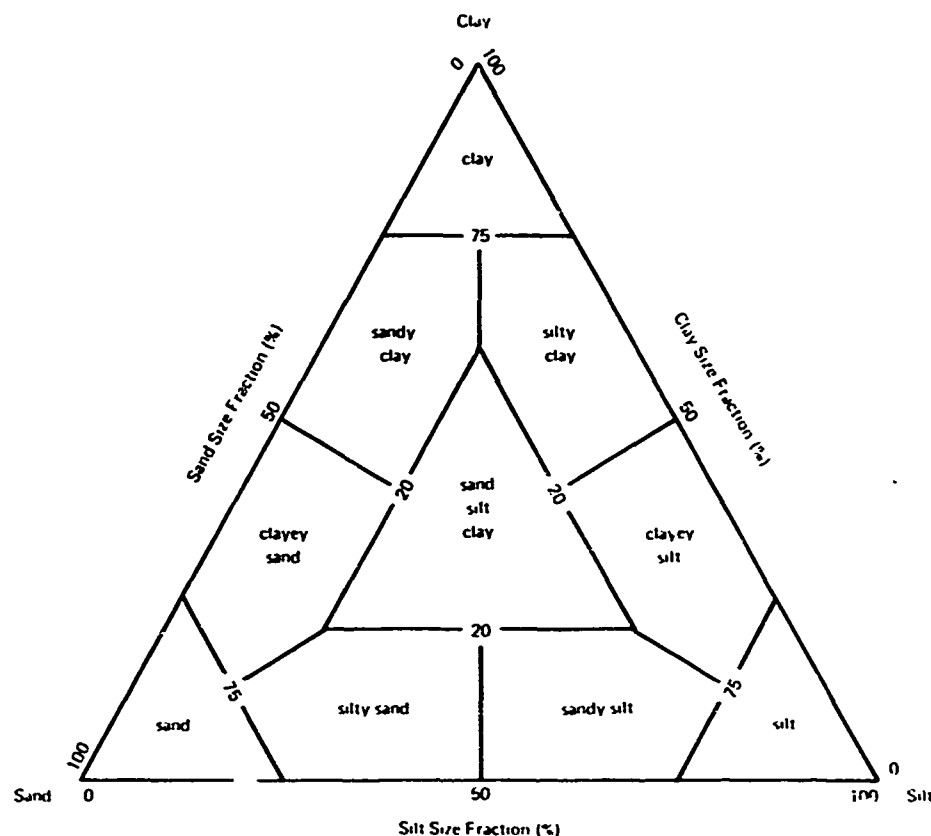

Figure A-1. Trilineal oceanic classification chart.

The sediments of the continental slopes and shelves are most diverse, and the sediment distribution is greatly affected by local topographic, geographic, and geologic features. It should be noted that rather large areas of the shelves and slopes are not covered by sediments; other areas have a relatively thin layer of sediment overlying bedrock. These areas are not indicated in Figure A-2, because they are too small to plot. About 60% of the continental

slopes is covered by silts, 25% by sand, 10% by gravel, and 5% by shells and ooze.[28] The sediment distribution on the continental shelves is so complex that any generalizations are likely to be misleading. One generalization appears valid—the classical hypothesis that the sediments grade uniformly from coarse to fine with increasing distance from shore is the exception rather than the rule. The predominant sediment on the shelves is sand; silt is the next most common sediment. Both the sands and silts are usually terrigenic; organic sands and silts are common in warm-water areas.

Table A-2. Percentage of Seafloor Covered by Sediments
(After Reference 42. © National Security
Industrial Association. Used by permission.)

Type of Deposit	Percentage of Seafloor	Average Depth (feet)
Terrigenic		
Shelf sediments	8	328
Mud (blue, green, volcanic, coral)	18	6,700
Pelagic		
Globigerina ooze (calcareous)	35	11,800
Pteropod ooze (calcareous)	1	6,600
Diatom ooze (siliceous)	8	12,800
Radiolarian ooze (siliceous)	2	17,400
Red clay	28	17,700

ENGINEERING PROPERTIES OF SEDIMENTS

Keller[43] has summarized the available data concerning the variation of sediment type, shear strength, water content, and wet unit weight in the North Atlantic and North Pacific Ocean basins. The data were taken from analyses of approximately 500 sediment cores (300 in the Atlantic, 200 in the Pacific). These cores ranged in length from 1 to 20 feet, with an average length of about 7 feet; the values of the respective parameters were averaged over the length of each core. Thus, the data represent only average values for the upper few feet of the seafloor and cannot be extrapolated to greater sediment depths unless some information is available on the variation of sediment properties with depth.
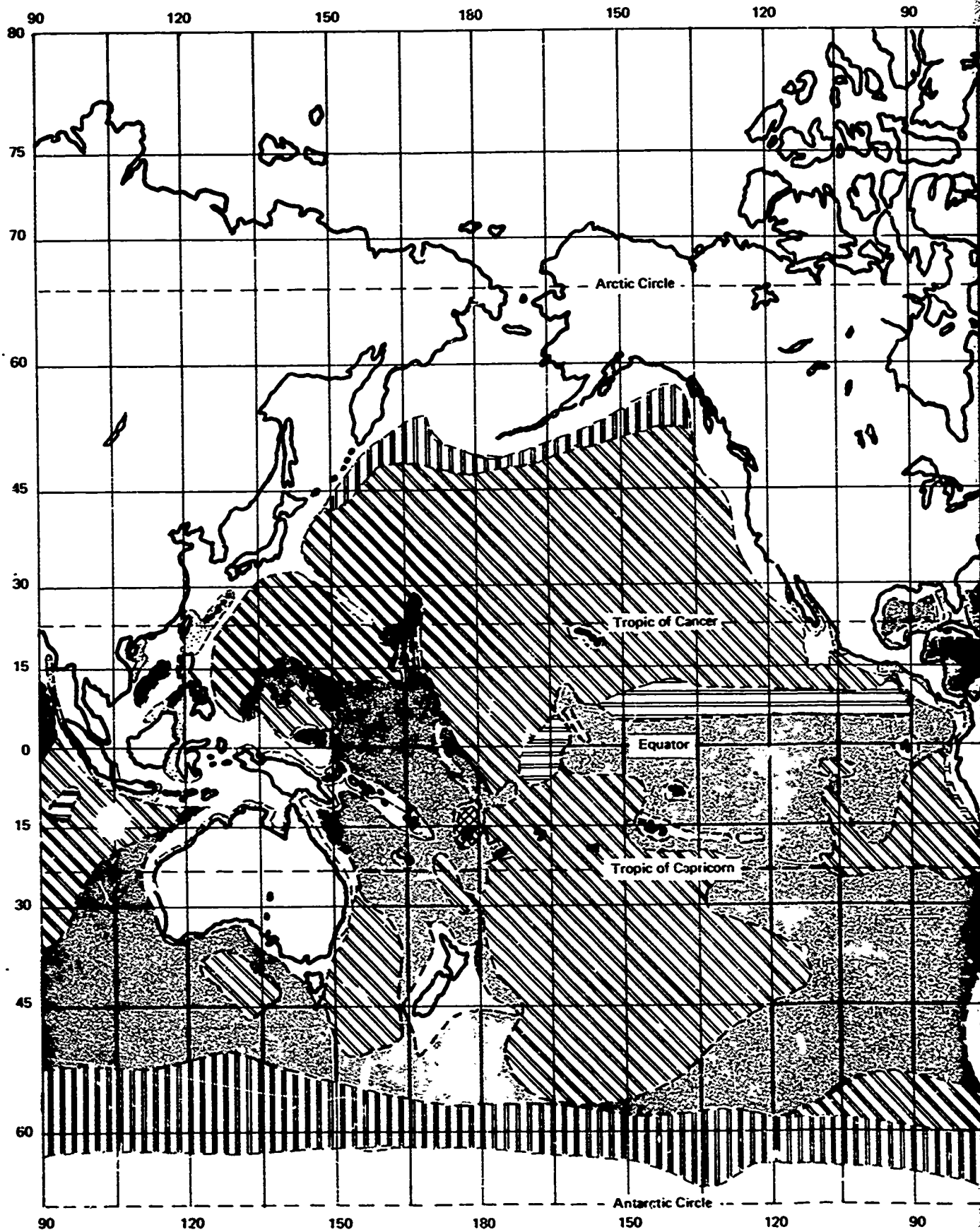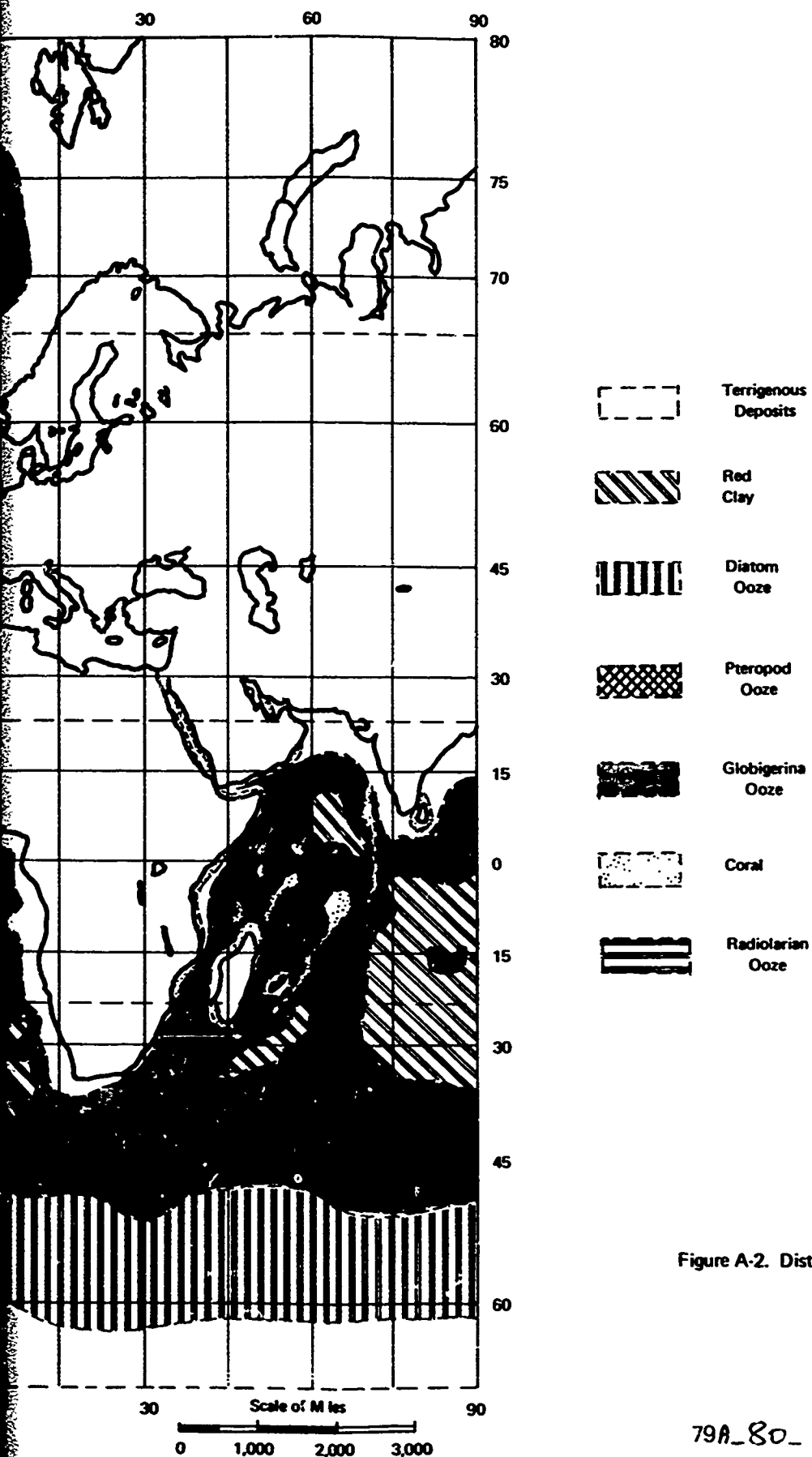
Figure A-2. Distribution of sediment types.

The data on shear strength are of particular interest, because this parameter controls the bearing capacity of the sediment. Most of the cores contained fine-grained cohesive sediments, with only a few stringers of fine sand. The shear strength of the sediment was taken to be equal to the cohesion, which was measured by either the laboratory vane shear test or the unconfined compression test. Keller's data indicate that the average shear strength of seafloor sediments ranges from about 0.25 to 2.5 psi, with the most common values lying between 0.5 and 1.5 psi. Shear strengths less than 0.5 psi are generally associated with deposits of red clay, and with coastal areas where the depositional environment is affected by local drainage and current conditions. The shear strength appears to increase with increased calcium carbonate content; that is, the highest shear strengths recorded in either basin are associated with deposits of calcareous ooze (1.0 to 1.5 psi in the Atlantic, 2.0 to 2.5 psi in the Pacific). Keller noted that locally high values of shear strength may occur within an area of low strength as a result of changes in bottom topography influencing the depositional environment; shear strengths on topographic "highs" are commonly slightly greater than the surrounding areas. Keller also concluded that, overall, the sediments of the North Atlantic basin are slightly stronger than those of the North Pacific.

The water content of the sediments was determined by the standard soil mechanics method, and was reported as the ratio, expressed as a percentage, of the weight of water to the weight of oven-dried solids in a given sediment sample. The water content values vary from 30 to 375%, but the most common ranges are 50 to 100% in the Atlantic and 100 to 200% in the Pacific. The higher water content values are generally associated with deposits of red clay; the lower values, with calcareous deposits.

The wet unit weight is the total weight per unit total volume of a sediment sample. The wet unit weight, or bulk density, of the sediments ranged from less than 78 pcf to about 125 pcf. The most common ranges of values were 78 to 94 pcf in the Pacific and 94 to 109 pcf in the Atlantic.

Keller's data are summarized according to sediment type in Table A-3. It is well to reemphasize that the data represent only average values for the upper few feet of the seafloor. It should also be noted that the data for shear strength and water content are probably lower-limit values, while the bulk-density data are probably upper-limit values. This is because of sample disturbance during coring and testing, and water loss from the sediment prior to testing. Thus, the data provide only a generalized picture of the variation of sediment type and properties to be expected on the seafloor. They are by no means sufficient for the final foundation design of a seafloor installation of more than nominal importance.

Table A-3. Engineering Properties of Various Sediment Types

Sediment Type	Shear Strength (psi)	Water Content (%)	Wet Unit Weight (pcf)
Terrigenic	0.04 to 2.5[a]	50 to 100	94 to 109
Red clay	<0.5	extremely variable, as high as 300	94 to 109[b] 78 to 94[c]
Siliceous	0.5 to 1.5	50 to 100	<94
Calcareous	0.5 to 1.0	100 to 200	94 to 109[b] 78 to 94[c]

[a] Among terrigenic sediments there are granular materials that have high strengths which cannot be stated in terms of shear strength.

[b] Atlantic sites.

[c] Pacific sites.

Relatively little information has been published concerning the compressibility or the consolidation characteristics of seafloor sediments. The data that are available indicate that seafloor sediments generally have large void ratios and high compressibility. Most fine-grained, inorganic sea-floor sediments appear to be normally consolidated; that is, there is no excess pore water pressure, and the sediments have never been subjected to loads greater than the existing overburden pressure. However, deep-ocean sediments often exhibit apparent overconsolidation as a result of interparticle bonds which develop either because of the slow rate of sedimentation or as a result of some form of chemical bonding.[27] The bonding causes the sediments to be stronger than would normally be expected. In areas where sediment has been eroded, the remaining material may exhibit true overconsolidated behavior. In areas of rapid deposition (such as off the mouth of large rivers), the sediments may be underconsolidated; that is, excess pore water pressures may be present in the sediment because the overburden pressure increases more rapidly than the excess pore pressure can dissipate. The available data indicate that the coefficient of consolidation and compression index of inorganic seafloor sediments generally fall within the range of values that have been found for terrestrial soils. However, because of the low effective stresses and large void ratios, the compressibilities of these soils are larger than terrestrial soils. The data also indicate that secondary compression can be much greater than is common for terrestrial soils. There are so few data concerning the compressibility and the consolidation characteristics of organic sediments (oozes) that no conclusions can be drawn; more research into the effects of organic matter is necessary.

Appendix B

MACROTOPOGRAPHY AND MICROTOPOGRAPHY
OF THE SEAFLOOR

INTRODUCTION

The topographic features of the seafloor can be divided into three broad categories: (1) macrotopography, (2) microtopography, and (3) surface roughness. The demarcations between the categories will arbitrarily be set at 60 feet (10 fathoms) and 5 feet; that is, features with vertical relief greater than 60 feet will be classified as macrotopographic features, and those with relief between 60 and 5 feet, as microtopographic features. Features with relief less than 5 feet are classed as surface roughness.

MACROTOPOGRAPHY

The major topographic features of the seafloor are: (1) the continental shelf, (2) the continental slope, (3) the continental rise, (4) the abyssal plains and hills, (5) oceanic ridges and rises, (6) trenches, and (7) volcanic cones. Superimposed upon these major features are numerous hills, ridges, basins, and valleys that can be classed as macrotopographic features. The major features, and the subfeatures common to each, will be described separately. Figures B-1 and B-2 illustrate the various major features of the seafloor.

Continental Shelf

The continental shelf can be described as the shallow flattish platform or terrace surrounding a continent. The seaward edge of the shelf, in almost all cases, is defined by a marked increase in gradient, called the shelf break. The width of the shelf, as well as the depth at which the maximum change in gradient occurs, is extremely variable. (The traditional definition of the shelf as the zone lying landward of the 600-foot depth contour only rarely coincides with the geological definition.)

Shepard[28] has presented average values of various shelf characteristics:

1. The continental shelf has an average width of 40 nautical miles.

2. The average depth at which the greatest change of gradient occurs at the shelf break is 72 fathoms.

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3. The average depth of the flattest portion of the shelves is about 35 fathoms.

4. Hills with a relief of 10 fathoms or more were found in about 60% of profiles crossing the shelves.

5. Depressions 10 fathoms or more in depth were indicated in 35% of the profiles. Many of these are basins, but others may represent longitudinal valleys.

6. The average gradient is 7 minutes; the slope is somewhat steeper in the inner than the outer half.

These averages were compiled from charts and profiles covering all parts of the world; measurements from the charts were made for each 10 miles along the shelf. Shepard cautions against the use of average values to describe a feature as irregular as the continental shelf; it appears that he is particularly concerned about the possible use of such averages as the basis for speculation on the origin and development of the shelves. The admonition is even more appropriate in relation to seafloor foundation engineering. In particular, local gradients much greater than the overall average of 7 minutes are known to exist; gradients as great as 5 degrees appear to be fairly common on the sides of the numerous hills, terraces, and depressions found on the shelf. The presence of these larger gradients may have a significant effect upon the design of the foundation for a seafloor installation, as well as the design of the installation itself. This point is discussed more completely in the main body of the report and in Appendix C.

Continental Slope

The relatively steep slope beyond the shelf break is called the continental slope. The outer edge of the continental slope is usually marked by a rather abrupt decrease in gradient. The continental slope is somewhat more regular than the continental shelf; in many cases, the slope extends virtually unbroken from the shelf break to the deep seafloor. However, hills, terraces, valleys, etc., are common. Also, zones at depths intermediate between the shelf and the deep seafloor may exist part way down the slope. These zones, called continental borderlands, may include mountain ranges and deep basins; the borderlands off Southern California are the best-known example. The general characteristics of the continental slope can be described as follows:

1. The average inclination of all continental slopes is 4 degrees 7 minutes.

2. The continental slopes of the Pacific Ocean average 5 degrees 20 minutes.

3. The continental slopes of the Indian Ocean average 2 degrees 55 minutes.

4. The continental slopes of the Atlantic Ocean average 3 degrees 5 minutes.

5. The continental slopes of the Mediterranean Ocean average 3 degrees 34 minutes.

6. The most prominent features modifying the continental slopes are steep-walled, V-shaped, deep submarine canyons.

Continental slopes can also be classified according to the type of coast:

1 Slopes off deltas and large rivers
    a. Mild inclination; average 1 degree 21 minutes
    b. Considerable number of hills and depressions
    c. Some valleys and large submarine canyons

2. Slopes off fault coasts
    a. Steep; average inclination 5 degrees 40 minutes; as great as 25 degrees
    b. Even in inclination and relatively smooth
    c. Submarine canyons rare, but small valleys common
    d. Inclination may increase with depth

3. Slopes off young mountain range coasts (other than fault coasts)
    a. Average inclination 4 degrees 40 minutes
    b. Slope cut by many submarine canyo

4. Stable coasts lacking large rivers
    a. Average inclination 3 degrees
    b. Slope inclination highly variable.
    c. Usually associated with a wide continental shelf
    d. Topography irregular and includes plateaus, valleys, canyons, hills, and depressions

The submarine canyons which cut across the continental slopes resemble river-cut mountain canyons on land. The walls are usually very steep; in some cases, vertical and even overhanging walls are known to exist.

Continental Rise

The continental rise is that portion of the seafloor that links the ocean-basin floor to the continental slope (see Figure B-1). In general, the continental rise is less steep than the continental slope. The seaward edge of

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the continental rise is generally marked by an abrupt change in slope. Here gradients change from values between 1:40 and 1:800, characteristic of the continental rise, to values less than 1:1,000. In some areas, no distinct break is seen, and the continental rise grades in an exponential form into the abyssal plain. The width of the continental rise varies from a few miles to as much as 400 miles. The continental rise is considered much smoother topographically than the continental slope; however, the rise is cut at many points by the lower end of the submarine canyons found on the continental slope. Typically, the continental rise has areas of extreme flatness (less than 1:1,000) interrupted by areas of irregular relief, often only a few fathoms in amplitude. Occasionally, the continental rise is punctuated by rather large seamounts, often linear in pattern.
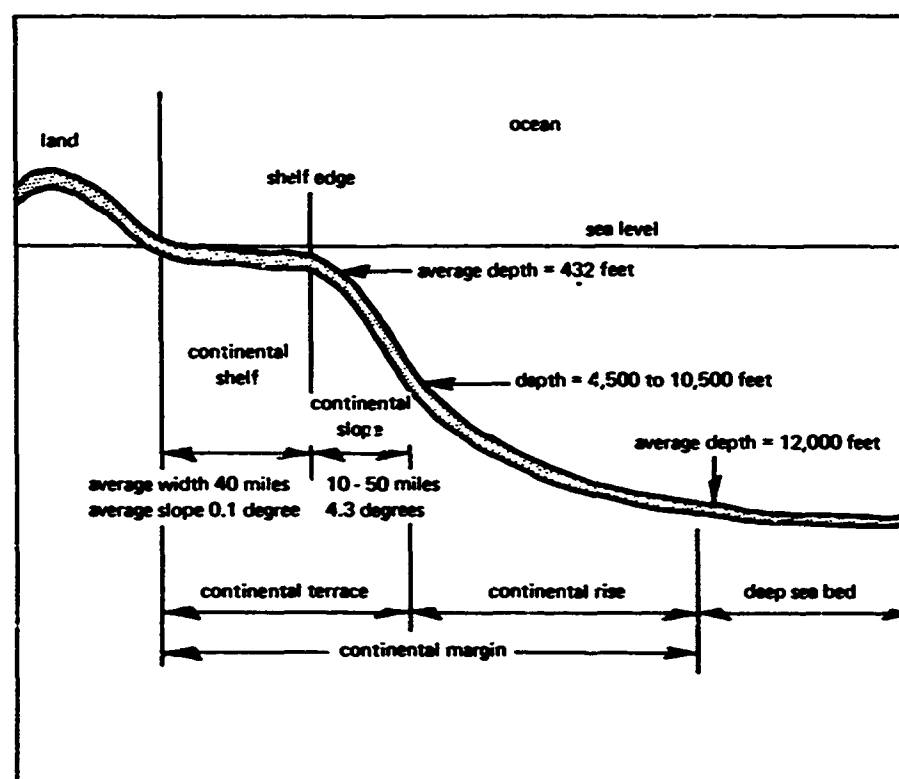

Figure B-1. Idealized profile of continental margin (vertical exaggerated).
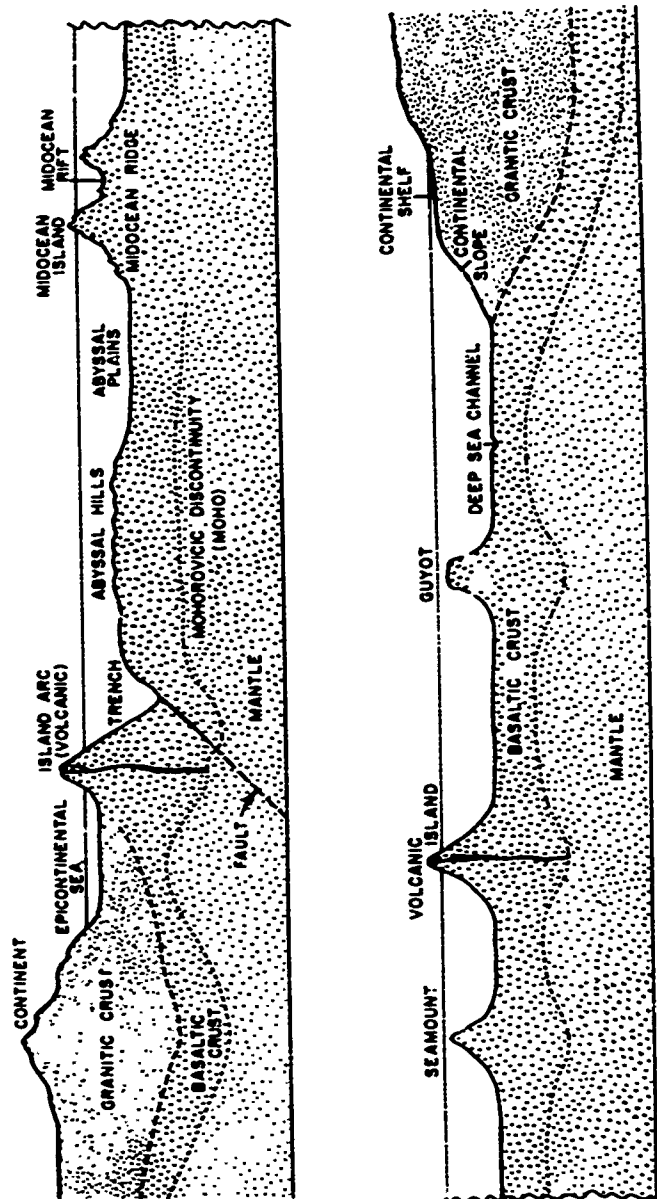(After Reference 44.)

Figure B-2. Cross section through typical ocean basin. (From "Handbook of Ocean and Underwater Engineering," edited by John J. Myers, Carl H. Holm, and Raymond F. McAllister. © North American Rockwell Corporation, 1969. Used with permission of McGraw-Hill Book Co.)

Abyssal Plains and Hills

An abyssal plain is an area of the ocean-basin floor in which the ocean bottom is flat and the inclination of the bottom is less than 1:1,000. An abyssal hill is a small, relatively sharply defined hill that rises in the ocean-basin floor to an elevation a few fathoms to a few hundred fathoms in height and is from a few hundred feet to a few miles in width. The term "abyssal hills province" is applied to those areas of the abyssal floor in which nearly the entire area is occupied by hills; that is, the province lies at approximately the depth of the adjacent abyssal plain but lacks a smooth surface.

Characteristically, abyssal plains lie at the base of the continental rise and have gradients which range from 1:1,000 to 1:10,000. It is generally agreed that abyssal plains are the result of an even blanket of sediment over a given area. Abyssal plain topography can be termed flat and featureless. Abyssal hills are generally found at the edge of abyssal plains away from the continental rise and are particularly common where trenches or ridges isolate ocean basins. Abyssal hills vary from 25 to 500 fathoms in height, and have been found, in many cases, to have relatively steep sides with local irregular small-scale volcanic topography.

Trenches

Trenches can be defined as long, narrow depressions of the deep seafloor with comparatively steep slopes and depths exceeding 3,500 fathoms. Trenches often parallel lines of volcanoes or island chains of volcanic origin. Most trenches are V-shaped. Some trenches have a sharp narrow bottom, but more commonly a flat floor of from a fraction of a mile to several miles in width is indicated. This flat bottom is usually attributed to sedimentary fill. Values of wall slope from 4 to 16 degrees have been recorded for a single trench.

Oceanic Ridges and Rises

Oceanic ridges are essentially continuous median elevations extending through the Atlantic, Indian, Antarctic, and South Pacific Oceans for a total distance of over 30,000 miles. The relief of the elevations above the adjacent ocean-basin floor is from about 550 fathoms to about 1,650 fathoms. The width of the elevations, known as the Mid-Oceanic Ridge, in most places is more than 500 nautical miles, and is essentially a broad, fractured swell occupying the center third of the oceans.

The various parts of the Mid-Oceanic Ridge have their own charac-
teristics. In the Southeastern Pacific, tne Ridge is very broad and is associated
with seismic activity, volcanoes and seamounts, whereas the Mid-Atlantic Ridge
is steep and narrow with volcanic islands and guyots (flat-topped seamounts).

It can be said that the Mid-Oceanic Ridge divides the major ocean
basins of the world. In addition, the main basins are further subdivided by
a number of transverse ridges and rises extending laterally from the central
ridge or out from bordering continents. The result is a complex network of
ridges which rival terrestrial mountain ranges in extent and relief.

To draw distinction between ridges and rises, the former are thought
of as elongated elevations with steep irregular slopes, whereas the latter have
smooth, broad, gentle sides. Also, oceanic rises are nonseismic, but oceanic
ridges are decidedly seismic in nature. As in the case of oceanic ridges, rises
are found throughout the major oceans of the world.

Volcanic Cones

Volcanic cones can be defined as isolated elevations of the deep
seafloor with an elevation of 500 fathoms or more in relief, and with com-
paratively steep slopes (steeper than land volcanoes) and relatively small summit
area. These volcanic cones can be divided into two groups: (1) the typical
pointed volcanic cones or seamounts, and (2) cones whose tops have been
eroded, called guyots or tablemounts. The difference in the pointed seamounts
and the flat-topped guyots is due to the elevation of the guyot above sea level
at some stage in its development, during which period it suffered subaerial ero-
sion. A given guyot's present depth below sea level is the result of subsequent
sinking and variations in sea level over time. The tops of many guyots are about
4,800 feet below the present sea level; the variation in depth is due primarily to
length of time of subsidence (that is, age).

The side slopes of seamounts and guyots, in most cases, are very steep.
Various investigators have indicated that average inclinations of up to 25 degrees
exist. This figure may be low when local areas are considered.

MICROTOPOGRAPHY

Superimposed upon the major topographic features of the world's
oceans are small features which can be termed microtopography and surface
roughness. These small features, ranging in size from less than an inch to 60
feet in vertical relief, cover virtually 100% of the seafloor.

The microtopography superimposed on the macrotopography of the continental shelf includes ripple marks, sand waves, rock outcrops, the trails and mounds of small seafloor animals, and small-scale, shallow, discontinuous depressions. Ripple marks and sand waves are found in areas of sandy bottom. Ripple marks are small, whereas sand waves may be up to 10 fathoms high, with a crest separation of up to about half a mile. Rock outcrops are found on the continental shelf throughout the world. The extent and relief of these outcrops may be several tens of feet. The marks left by bottom-crawling and burrowing seafloor animals are widespread on the continental shelf. Where large populations of these animals are found, the bottom may be churned up with mounds up to 6 inches or more in height spread over a wide area. The depressions found on the continental shelf are generally shallow flanks which vary from steep, rough, exposed rock to gentle, smooth, sediment-covered slopes.

Beyond the continental shelf, the continental slope, with its many canyons, begins. In many places, the continental slope is smooth and gentle because of a blanket of sediment. These smooth areas exhibit much the same microrelief as is found on the continental shelf. Where canyons cut the slope, very steep or even overhanging rock walls may occur. In addition, many small tributary canyons are sometimes found in the vicinity of the deep main canyons. These smaller canyons are usually a mile or less in width, a few miles long, and a few fathoms deep.

The microtopography of the continental rise and abyssal plain appears to be quite similar. On the continental rise, hills a few fathoms high and considerable distance apart are present. On the abyssal plain, undulations a few feet in height and several miles apart are present. Both these major features may be cut by the lower end of canyons. However, as the canyons reach to deeper parts of the seafloor they become less steep and rugged and tend to merge with broad depressions. Also, the bottom shows the signs of seafloor animals. Tracks, trails, mounds, and depressions a few inches in extent and relief are found throughout the sediment-covered seafloor of the plains and rises. The ripple marks and sand waves of the continental shelf are less prominent here because the sandy material required for their foundation has been largely replaced by clay and ooze with higher cohesion. Chemical precipitates, in the form of manganese nodules, are found on extended abyssal areas and deep sea basins of all major oceans. These nodules, which average about 2 inches in diameter, constitute an important feature of deep sea microtopography where they occur.

The oceanic ridges and seamounts display many similar microtopographic features. Both show exposed bedrock, steep boulder-covered slopes, and pockets of sediment. The central rift valley of the Mid-Atlantic Ridge and

various seamounts have been found to contain deposits of pillow lava which produce microtopographic features several inches to a few feet in relief. Manganese nodules are also a common feature of oceanic ridges and seamounts. The frequent appearance of ripple marks in the sediments of seamounts indicates that high concentrations of sand material are present.

The world's trenches show generally steep flanks, which may be without minor relief and are highly variable in inclination. The bottom of a trench may be filled or partially filled with sediment, resulting in a micro-topography that ranges from flat sedimented bottoms with biogenic mounds and trails to sediment-free, rough, rock-strewn bottoms.

Shipek[46] has analyzed several hundred photographs, made by the Navy Electronics Laboratory (now Naval Electronics Laboratory Center) in connection with studies of the acoustic reflectivity of the seafloor, to determine the nature and extent of the surface roughness of the seafloor. Shipek concluded that surface roughness generally is directly related to the intermediate and major topographic relief upon which it is superimposed; for example, where the topography is rough, the seafloor surface is generally rough. Shipek also noted that, with some exceptions, surface roughness decreases with increasing depth. Table B-1, taken from Shipek's paper, indicates the relative surface roughness that exists on the various types of topographic features. Table B-2 gives the rating scale used, and indicates the magnitude of roughness that may be expected. Table B-3 shows the causes of surface roughness and indicates that the most prevalent is the presence of marine animals.

A complete summary and discussion of macrotopography and microtopography, including surface roughness, and their influence on the selection and design of a foundation is located in the main body of this report in the subsection entitled Topography (under FOUNDATION DESIGN CONSTRAINTS).

Table B-1. Numerical Scale of Seafloor Microroughness (From Reference 46)

Feature	Numerical Rating of the Relief*
Canyon—inner	5
Bank	4
Irregula. topography	4
Small local ridge	4,3
Island slope	4,2
Local ridge	3,4
Side slopes of trough	3
Low hills	3
Topographic high	3
Island shelf	3,2
Seamcunt surface	3,2
Irregular topogiaphy	3,2
Island slope	2,4
Seamount surface	2,3
Island shelf	2,3
Irregular topcgraphy	2,3
Basin	2
Canyon—outer	2
Continental slope	2
Sill	2
Valley	2
Rift valley	2
Gentle relief (275-meter hills)	2
Irregular hills (180-meter relief)	2
Intermountain valley	2
Abyssal hills	2
Gentle topography	2,1
Gentle topography	1,2
Saddle	1
Slope	1
Sea valley	1
Smooth topography	1
Flat topography	1

* See Table B-2 for rating scale descriptions.

Table B-2. Descriptive Notes for Rating Scale of Seafloor
Microroughness (After Reference 46)

Because the seafloor is never perfectly flat, the rating zero is not used.
The rating 1 denotes minimum but recognizable roughness; the rating 5 denotes
maximum roughness. Some descriptive notes on the ratings follow:

1. Almost smooth surfaces formed on clays, oozes, and silty clays
in abyssal areas between, and on, major and intermediate topographic features.
Visible evidence of churning is lacking, with a minimum of epifauna and infauna
present. Rock fragments and manganese nodules occur in scattered patches, varied
according to chemical composition of water.

Height of churning: 1 inch
Normal range of microrelief: 0 to 4 inches

2. Low-order bottom relief formed by fauna churning on clays, oozes,
and silty clays in areas of gentle relief. Such low-order relief also occurs on marine
slopes, valleys, basins, and other gentle topographic features. More epifauna visibly
present but not in great numbers in deeper areas. Occasional occurrences of small
manganese nodules and rock fragments in tightly packed or scattered patterns of
distribution, again dependent on seawater conditions. Occasional occurrences of
loosely scattered and larger manganese nodules with visible churning between tar-
gets. Oozes are normally in shoaler areas and are coarser grained.

Height of churning: 1 to 2.5 inches
Normal range of microrelief   1 to 8 inches

3. Maximum churning of clay and silty sediments. Ripple marks occur
where fine sands and sandy silts are present. Greater occurrence of larger manga-
nese nodules, pumice slabs, and rock fragments. Chemical crusting of sediments
sometimes present. Major and intermediate features predominatly island slopes,
hills, ridges, highs, and irregular topography.

Height of churning: 2.5 to 6 inches
Normal range of microrelief: 2.5 inches to 1 foot

4. Rock fragments, outcrops, boulders, and coarse sediments predomi-
nate in this shoaler environment. Fauna churning maximum where silty sediments
exist. Ripple marks often present in sandy sediments. Greater abundance of epi-
fauna on rocky surfaces.

Height of churning, where present: 6 inches
Normal range of microrelief: 2.5 to 39 inches

5. Jagged rocks, phosphorite nodules, large boulders, and coarse
sediments on upper surfaces and slopes of underwater features such as ridges,
mountains, banks, cliffs, walls of canyons, and other topographic highs. Fauna
churning of coarse sediments variable and dependent on presence of organic mat-
ter. Predominance of attached and unattached epifauna on rock exposures.

Height of churning: highly variable, up to 6 inches
Normal range of microrelief: i inch to 10 feet

Table B-3. Distribution and General Relationships of Underwater Topographic Relief (After Reference 46)

(Note: Shaded areas indicate principal forms of microrelief found on major topographic features.)

| Major Relief	Intermediate Relief	Microrelief				
		Outcrops	Chemical Disturbance	Benthonic Animals	Biological Disturbance	Physical Disturbance
Continental	bank	▨		▨	▨	
	basin		▨	▨	▨	
	canyon	▨		▨	▨	▨
	island shelf	▨		▨	▨	▨
	continental slope			▨	▨	
	sill			▨	▨	
	...e			▨	▨	
	trough	▨		▨	▨	
	valley			▨	▨	
	rift valley			▨	▨	
Ridge	basin		▨	▨	▨	
	gentle relief			▨	▨	▨
	island shelf	▨		▨	▨	
	seamount surface		▨			▨
Gulf of California	basin	▨		▨	▨	
	canyon	▨		▨	▨	▨
	island shelf	▨		▨	▨	
	small local ridge	▨		▨		
Fracture zone	basin		▨	▨	▨	
	irregular hills		▨	▨	▨	
	gentle topography		▨	▨	▨	
	irregular topography		▨		▨	
Abyssal plain	gentle topography	▨		▨	▨	▨
East Pacific rise	island slope	▨		▨		
	low hills	▨	▨	▨		
Central Indian rise	island slope	▨		▨		▨
Deep sea basin	low hills		▨	▨	▨	
	gentle topography		▨	▨		
Trench	gentle topography			▨	▨	
	local ridge	▨	▨	▨	▨	
	flat topography			▨	▨	
Rift mountains	topographic high	▨	▨		▨	▨
	intermountain valley			▨	▨	
Seamount province	abyssal hills		▨	▨	▨	
	seamount surface		▨			▨
	irregular topography	▨	▨			
Beaufort Sea	slope			▨	▨	
	sea valley			▨	▨	
	smooth topography			▨	▨	

Appendix C

ANALYSIS OF COST VERSUS TOPOGRAPHIC ACCURACY—
AN EXAMPLE

This appendix summarizes an exercise to gain an idea of the value of improved topographic accuracy to the foundation designer. The example used is a small "simple" mat foundation. The exercise is as follows. Assume that three structures are to be placed on the seafloor in 1,000 feet of water. The structures are (1) a STU-type structure, see Figure 2, (2) a manned habitat, and (3) a highly sensitive, multiple hydrophone array that must be maintained within approximately 15 minutes of vertical. Assume that all three structures have the same negative buoyancy and that a mat foundation 10 feet square is sufficient to prevent excessive settlement or a bearing capacity failure.

The foundation requirements, as related to topography, can be summarized as follows:

1. If any of the structures is placed on an inclination greater than 1/10 (vertical/horizontal), a local slope stability failure may occur. Therefore, this inclination is an absolute maximum that can be tolerated.

2. If any of the structures is placed on an inclination between 1/20 and 1/10, the structure may "skid" down the incline, and some sort of "key" must be attached to the mat to prevent the skidding.

3. If the manned habitat is placed on an inclination greater than 1/50, a leveling system must be provided between the mat and the habitat module for the comfort of the inhabitants. (Certain experience indicates that slopes of about 1 degree, or 1/50, are not too noticeable by humans; greater slopes cause them to feel uneasy and perhaps unsafe.)

4. If the hydrophone array is placed on an inclination greater than 1/250, a sensitive leveling system must be provided. (Such a degree of accuracy may be more than is actually required for such equipment. However, the hypothetical case serves as a good example of the nature of the problem.)

The inclination of the structure can be expressed as Δ/B', where B' is the minimum overall lateral dimension (in this case, 10 feet), and Δ is the difference in elevation in this distance. Figure C-1 shows this relationship for a mat and a spread footing foundation.

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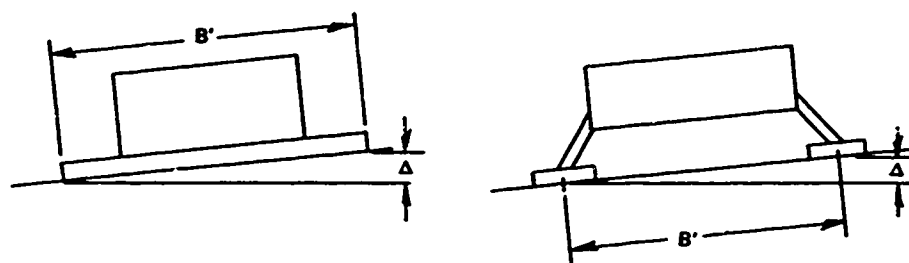
B' = minimum overall lateral dimension
L = maximum overall lateral dimension
Δ = differences in elevation
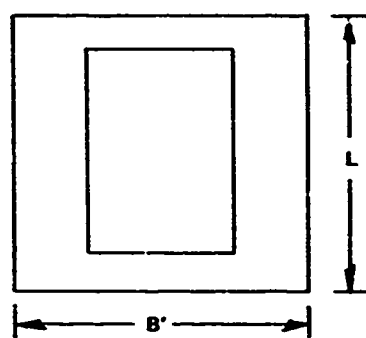
Mat Foundation
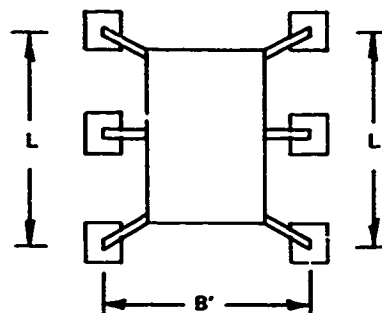
Spread Footing Foundation

Figure C-1. Minimum overall lateral dimension for mat and spread footing foundations.

The accuracy of a topographic mapping system is a function of the minimum change in vertical relief which it can detect. In the case of the example, it is possible to express this accuracy in terms of Δ/B'; that is, the minimum inclination that can be measured with a high degree of confidence.

Cost estimates for the foundation are as follows and do not include costs of topographic survey, site survey, or soil properties determination:

10 x 10-foot concrete slab	$ 2,000
Perimeter key	1,000
Leveling system, manned habitat	7,000
Leveling system, hydrophone array	10,000

Installation—Mat, mat with key	$ 2,000
—Mat with manned leveling system	4,000
—Mat with hydrophone leveling system	6,000

These cost estimates are admittedly rough. However, it is believed that they are of the correct order of magnitude and are sufficiently accurate to illustrate the trend of costs. Higher costs are involved in the installation of either of the leveling systems, because of the need to telemeter data to the surface. The cost estimates can be combined to provide the following list of total costs:

Mat	$ 4,000
Mat with key	5,000
Mat with manned habitat leveling system, without key	13,000
Mat with manned habitat leveling system, with key	14,000
Mat with hydrophone leveling system, without key	18,000
Mat with hydrophone leveling system, with key	19,000

The total costs can now be compared to the topographic accuracy in the following manner: Tables C-1, C-2, and C-3 show the total costs for each foundation in terms of both the actual maximum inclination (Δ/B') existing at a site and the accuracy of the measured maximum inclination. For example, consider Table C-3. Assume that the actual maximum inclination existing at the site is 1/250. If the topographic accuracy is 1/250 then we can provide the hydrophone array with only a simple mat foundation at a cost of $4,000. If, however, the accuracy is only 1/20, we must assume that the structure will land on an inclination of 1/20, and must provide the leveling system, for a total cost of $18,000. If the accuracy is only 1/10, we must further assume that the structure will skid, and must provide a "key," for a total cost of $19,000. For these latter two cases the costs for topographic inaccuracy were $14,000 and $15,000, respectively.

The additional costs incurred as a result of inaccurate topographic data can be illustrated as follows. Divide the cost of the foundation that must be provided because of lack of accuracy by the cost of the foundation that is actually required (the foundation that we could provide if the accuracy were great enough). This will be a number equal to, or greater than, unity. Plot this ratio versus the measured inclination; that is, the topographic accuracy. This must be done for each row of the foregoing tables. The plotted points for each actual maximum inclination can be connected by straight lines; the slope of the lines is an indication of extra costs. The use of straight lines does not imply a straight-line relationship between accuracy and costs, but is a matter

of convenience. The true relationship is probably a form of step function. Figures C-2, C-3, and C-4 show these plots for Tables C-1, C-2, and C-3, respectively.

Table C-1. Foundation Cost as Function of Actual Inclination and Accuracy of Measured Inclination (STU Structure)

Actual Maximum Inclination	Accuracy of Measured Inclination	Foundation Cost ($)
1/250	1/250	4,000
	1/50	4,000
	1/20	4,000
	1/10	5,000
1/50	1/250	4,000
	1/50	4,000
	1/20	4,000
	1/10	5,000
1/20	1/250	4,000
	1/50	4,000
	1/20	4,000
	1/10	5,000
1/10	1/250	5,000
	1/50	5,000
	1/20	5,000
	1/10	5,000

Table C-2. Foundation Cost as Function of Actual Inclination and Accuracy of Measured Inclination (Manned Habitat)

Actual Maximum Inclination	Accuracy of Measured Inclination	Foundation Cost ($)
1/250	1/250	4,000
	1/50	4,000
	1/20	13,000
	1/10	14,000
1/50	1/250	4,000
	1/50	4,000
	1/20	13,000
	1/10	14,000
1/20	1/250	13,000
	1/50	13,000
	1/20	13,000
	1/10	14,000
1/10	1/250	14,000
	1/50	14,000
	1/20	14,000
	1/10	14,000

Table C-3. Foundation Cost as Function of Actual Inclination and Accuracy of
Measured Inclination (Hydrophone Array)

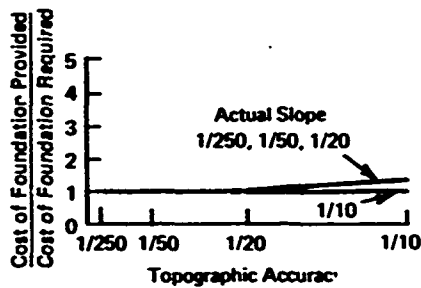| Actual Maximum Inclination	Accuracy of Measured Inclination	Foundation Cost ($)
1/250	1/250	4,000
	1/50	18,000
	1/20	18,000
	1/10	19,000
1/50	1/250	18,000
	1/50	18,000
	1/20	18,000
	1/10	19,000
1/20	1/250	18,000
	1/50	18,000
	1/20	18,000
	1/10	19,000
1/10	1/250	19,000
	1/50	19,000
	1/20	19,000
	1/10	19,000

Figure C-2. Foundation cost increase versus topographic accuracy (STU structure).
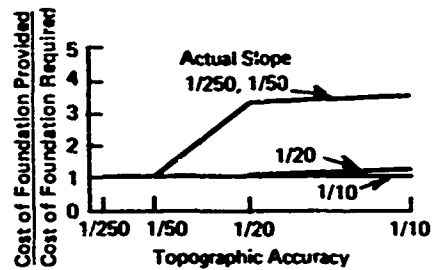

Figure C-3. Foundation cost increase versus topographic accuracy (manned habitat).
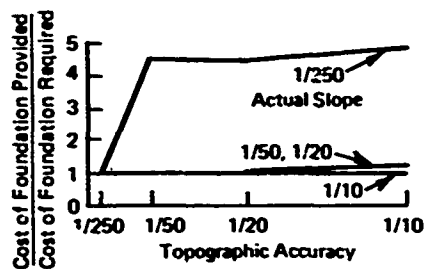

Figure C-4. Foundation cost increase versus topographic accuracy (hydrophone array)

The foregoing illustrates the complexity of a cost-related analysis of topographic accuracy requirements for a single foundation; that is, a 10 x 10-foot mat. The total costs are seen to be a function of the type of structure, the interfacing between the structure and the foundation, and the actual inclination of the site. The absolute accuracy, expressed in feet, is also a function of structure size; that is, for the example foundation, an inclination of 1/10 requires an absolute accuracy of 1 foot. For a 5 x 5-foot foundation and the same inclination, an absolute accuracy of 0.5 foot is required. Furthermore, the inclination of the structure might be caused by several circumstances. For instance, at an otherwise level site, a shallow pit or low mound may exist with a local slope of 1/10. If the structure lands on this surface irregularity, the required foundation is more expensive than would be necessary at other locations within the site. Therefore, a thorough and highly reliable cost-related analysis would require a study of the probability of occurrence of the given inclinations on the seafloor, and a study of the probable size and nature of structures that will be placed on the seafloor. Such an analysis would be expensive. Several simplified analyses of the type described herein can be performed to provide an idea of the cost trends. Because of the nature of the assumptions that must be made, high confidence cannot be placed in the actual quantitative results, but the trends should be fairly accurate.

At least two other assumptions are implicit in the foregoing analysis. The first assumption is that the ratio of the height of the structure to the minimum overall lateral dimension is not so great that the structure is in danger of overturning if it lands on an inclination. The second assumption is related to the stresses induced in a structure because of inclination. Research indicates that a permissible inclination for a simple steel frame is on the order of 1/200; because this is a "permissible" ratio, there is, of course, some factor of safety implied. It has therefore been assumed that the stresses induced by inclination can be accommodated by the structure, the mat, and the interfacing between them.

Appendix D

POSITIONING SYSTEMS

Numerous methods and pieces of equipment are well developed for determining the position of a ship, or other object, on the surface of the ocean. These are summarized in Table D-1. This table also includes data on the range and accuracy of each system. Systems and methods for determining the position of objects in the water column or on the seafloor are summarized in Table D-2. This table includes some systems which both determine and control position.

Table D-1. Surface Positioning Systems

System	Range (nm)	Accuracy (ft)		No. of Transmitters	Remarks
		Optimum	At Maximum Range		
LORAN-A (standard)	750	1,500	3,000	3	Replaced by LORAN-C.
LORAN-B	250	45	300	3	
LORAN-C	1,500	70	2,500	3	Range varies with weather and sky waves.
LORAN-D	–	60	500	3 or more	Transmitters moored at sea. Accuracy directly proportional to number of stations.
LORAC-A	200	15	400	3	Excellent repeatability.
LORAC-B	300	15	400	4	
LORAC-C	1,200	–	1 in 5,000	3	
DECCA	425	25	250	2	Expensive. Cost, $120,000.
Two-Range DECCA	150	30	50	2	Similar to DECCA Navigator.
DECCA Navigator	250	1,500	1,200	3	Range and accuracy affected by sky waves.
DECCA Survey	200	25	300	3	Cost of system, $100,000. Refinement of DECCA Navigator.
DECCA Minifix	25	25	300	3	Very portable system.
DECCA Sea-Fix	25	25	300	3	Transmitters mounted in buoys for moored operations.
SHORAN	30 to 40	30	50	2	Line-of-sight limited.
HIRAN	500	25	50	2	Improved SHORAN system.
MORAN	15 to 30	20	50	2	Very portable.
SHIRAN	450	10	–	4	Primarily designed for use in aircraft. Line-of-sight operation.
AERIS II	54	2	6	2	
RAYFLEX	40	2	–	2	Combines navigation radar with primary positioning radar.

Table D-1. Continued

System	Range (nm)	Accuracy (ft)		No. of Transmitters	Remarks
		Optimum	At Maximum Range		
DMRAYDIST	200	12	100	2	Cost. $75,000. Can be used by more than one vessel at a time.
HYDRODIST	25	12	100	2	Line-of-sight limited.
RPS-1 (range positioning system)	25	–	50	2 or more	Compatible with existing radar. Easy to operate. Low maintenance cost. Components small and lightweight. All-weather operation.
RPS-2	25	–	33	2 or more	Not compatible with existing radar. Easy to operate. Small, lightweight components. All-weather operation.
RPS-3	50	–	50	2 or more	Line-of-sight operation. All-weather. Small, lightweight components.
RANA	100	50	100	3	French system similar to LORAC.
Electronic position indicator	500	200	1,500	2	Can be used by more than one vessel by time sharing only.
OMEGA	1,400 at present; unlimited when fully deployed	3,000	7,200	4 at present; 8 at completion	Base-line length, ionospheric disturbances affect accuracy. Shipboard equipment small and lightweight (1.5 cubic feet, 75 pounds).
Optical means (sextant)	30	1 in 2,000	–	2 or more	Weather limited.
Celestial navigation (unautomated)	unlimited	6,000	12,000	–	Cloud cover, precipitation, and fog prevent operation. Small inexpensive system.
Celestial navigation (automated)	unlimited	3,000	6,000	–	Has same limitations as unautomated system with respect to weather. Cost. $30,000 to $50,000.
Inertial navigation	unlimited	<3,000	–	–	System yields continuous log of position. Accuracy decays with time if system not used with second system that corrects errors.

Table D-1. Continued

| System	Range (nm)	Accuracy (ft)		No. of Transmitters	Remarks
		Optimum	At Maximum Range		
Satellite navigation	unlimited	150 to 500	–	–	Subject to ionospheric, azimuth angle, and Doppler related errors. Coverage not continuous. User equipment expensive, heavy, bulky.
Doppler	unlimited	0.1% of distance traveled	–	–	Self-contained system of navigation that provides a continuous plot of location. Accuracy decreases with distance.
Radio acoustic ranging	30	300	5,000	2 on seafloor	Accuracy depends on ability to calculate velocity of sound in water.
Topographic	unlimited	few hundred feet	–	–	Sensing instruments on ship compare output with stored maps to determine positions. Area involved must have been previously charted and must have sufficient relief for use as navigational aid.
Dead reckoning and estimated position	unlimited	–	–	–	Accuracy depends on experience of navigator.

Table D-2. Surface-to-Bottom Positioning Systems

System	Remarks
Submersibles	Accuracy of better than 1 inch possible for light loads (100 to 200 pounds) at depth of 6,000 feet. Expensive with current submersibles.
Guide wires	Accuracy of better than 9 inches reported by oil industry in depths to 1,300 feet. Cable entanglement a serious unsolved problem. Depths of 2,000 to 3,000 feet possible in near future.
Bottom-supported winches	Accuracy of better than 1 foot at 6,000 feet within state-of-the-art.
Surface-supported winches	Accuracy of better than 1 inch possible at present to depth of 2,700 feet and weight of 10,000 pounds. Capability to 6,000 feet possible in near future.
Seafloor acoustic beacon	Accuracy of better than 1 foot with load-mounted beacon. 1 to 2% of water depth without (to 18,000 feet).
Bottom crawler	Accuracy of better than 1 inch possible. Still experimental and for shallow depths.
Echo-ranging sonar	Accuracy of better than 1 foot shown in experimental tests in shallow water.

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Appendix E

**EXAMPLES OF CANDIDATE FOUNDATION CONFIGURATIONS
AND EXPECTED PERFORMANCE**

Physical Configuration
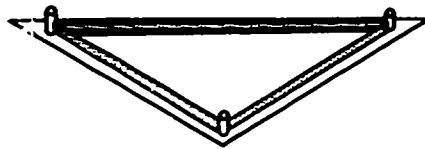
Triangular Strip Footing

Side length: 12 feet
Footing width: 1.25 feet
Submerged weight: 200 pounds

Design Characteristics and Constraints

Reliability: 0.90
Sensitivity: <15 degrees
Load capacity: <4,000 pounds
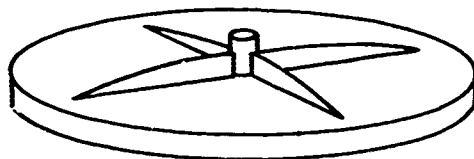
Size: <12 feet
Soil: sand
Topography: <4 degrees

Currents: <0.5 knot
Emplacement: single module

Expected Performance

Soil	Sand
Safety factor	3.1
Settlement	0.25 inch
Tilting	0.25 degree
Lateral resistance	1,200 pounds
Uplift resistance	0
Minimum load	0

Figure E-1. Simple spread footing

Physical Configuration

Circular Footing

Diameter: 9 feet
Edge depth: 0 to 1.5 feet
Submerged weight: 500 pounds

Design Characteristics

Reliability: 0.90
Sensitivity: <15 degrees
Weight: <4,000 pounds

Size: <12 feet
Soil: weak cohesive to competent cohesive

Topography: <10 degrees
Current: >0.5 knot
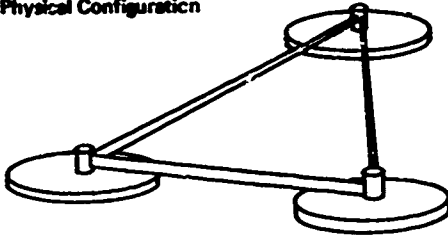Emplacement: single module

Expected Performance

Remarks: Load must be centered.

Soil	Weak	Competent
Safety factor	2.7	14
Settlement	13 inches	6 inches
Tilt	4 degrees	2 degrees
Lateral resistance	1,100 pounds	3,500 pounds
Uplift resistance	<4,000 pounds	<2,000 pounds
Minimum load	1,000 pounds	1,000 pounds

Figure E-2. Keyed spread footing.

Physical Configuration

Tripodal Articulated Footings

    Spacing: 40 feet
    Submerged weight: 4,000 pounds

Individual Footings

    Diameter: 10 feet
    Edge depth: 0.5 to 0 feet

Design Characteristics and Constraints

Reliability: 0.999	Size: >40 feet	Current: >0.5 knot
Sensitivity: <5 degrees	Soil: competent cohesive and sand	Emplacement: single module
Load capacity: $<40,000$ pounds	Overall slope: <4 degrees	

Expected Performance

Soil	Competent	Sand
Safety factor	9	32
Settlement	4 inches	0.5 inch
Tilt	0.5 degree	0
Lateral resistance	13,000 pounds	13,000 pounds
Uplift resistance	$<40,000$ pounds	0
Minimum load	9,000 pounds	0

Figure E-3. Multiple spread footing.

Physical Configuration
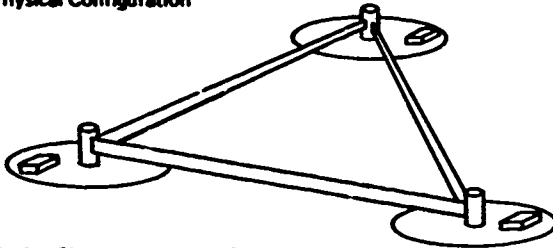
Tripodal Articulated Footings

    Spacing: 40 feet
    Submerged weight: 5,000 pounds

Individual Footings

    Diameter: 10 feet
    Edge depth: 1.0 foot

Design Characteristics and Constraints

Reliability: 0.999	Size: >40 feet	Overall slope: <10 degrees
Sensitivity: <5 degrees	Soil: weak cohesive and competent	Current: >0.5 knot
Load capacity: 40,000 pounds	cohesive	Emplacement: multimodule

Expected Performance

Remarks: Equipment not yet developed.

Soil	Weak	Competent
Safety factor	7	9
Settlement	12 inches	2.5 inches
Tilt	1 degree	0.4 degree
Lateral resistance	11,000 pounds	14,000 pounds
Uplift resistance	85,000 pounds	100,000 pounds
Minimum load	0	0

Figure E-4. Multiple preconsolidating footing.

Physical Configuration
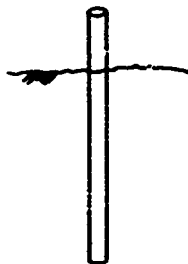
Pile diameter: 12 inches
Depth of embedment: 40 feet
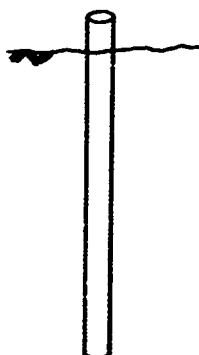Submerged weight: 2,000 pounds

Design Characteristics and Constraints

Reliability: 0.90
Sensitivity: $<$ 15 degrees
Load capacity: $<$ 4,000 pounds
Size: $<$ 12 feet
Soil: weak cohesive to sand
Overall slope: $>$ 10 degrees
Current: $>$ 0.5 knot
Emplacement: multimodule

Expected Performance

Soil	Weak	Sand	
Safety factor	3.5	9.0	Remarks: Installation
Settlement	3 inches	0.5 inch	equipment not yet
Tilt	3 degrees	3 degrees	developed.
Lateral resistance	6,000 pounds	10,000 pounds	
Uplift resistance	6,000 pounds	10,000 pounds	
Minimum load	0		

Figure E-5. Single pile, low capacity.

Physical Configuration

Pile diameter: 24 inches
Depth of embedment: 80 feet
Submerged weight: 10,000 pounds
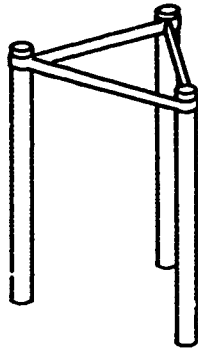
Design Characteristics and Constraints

Reliability: 0.99
Sensitivity: $<$ 5 degrees
Load capacity: 40,000 pounds
Size: $<$ 40 feet
Soil: weak cohesive to sand
Overall slope: $>$ 10 degrees
Current: $>$ 0.5 knot
Emplacement: multimodule

Expected Performance

Soil	Weak	Sand	
Safety factor	3.8	16	
Settlement	10 inches	0.5 inch	Remarks: Installation
Tilt	3 degrees	3 degrees	equipment not yet
Lateral resistance	14,000 pounds	26,000 pounds	developed.
Uplift resistance	50,000 pounds	150,000 pounds	
Minimum load	0	0	

Figure E-6. Single pile, medium capacity.

Physical Configuration

Equilateral Triangular Group

    Pile spacing: 40 feet
    Submerged weight: 25,000 pounds

Individual Piles

    Pile diameter: 16 inches
    Depth of embedment: 80 feet

Design Characteristics and Constraints

Reliability: 0.999   Size: >40 feet   Current: >0.5 knot
Sensitivity: <1 degree   Soil: competent cohesive and sand   Emplacement: seafloor construction
Load capacity: 40,000 pounds   Overall slope: <4 degrees

Expected Performance

Soil	Competent	Sand	
Safety factor	11	26	
Settlement	8 inches	0.5 inch	Remarks: Installation
Tilt	0.5 degree	0	equipment not
Lateral resistance	23,000 pounds	60,000 pounds	yet developed.
Uplift resistance	150,000 pounds	150,000 pounds	
Minimum load	0	0	

Figure E-7. Multiple piles.

Physical Configuration
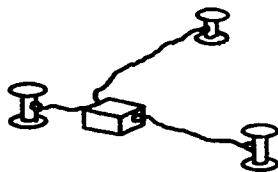
Individual Levelers

    Compression: 30,000 pounds
    Tension: 30,000 pounds
    Shear: 15,000 pounds
    Adjustment: 2 feet

Design Characteristics and Constraints

Reliability: 0.999   Size: >40 feet   Current: >0.5 knot
Sensitivity: 0.5 degree   Soil: competent cohesive and sand   Emplacement: seafloor construction
Load capacity: 40,000 pounds   Overall slope: <4 degrees

Remarks: Only initial leveling required.

Figure E-8. Structure—foundation interfacing.

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